REPORT DOCUMENTATION PAGE

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AD-A211 232

TIC
LECTE
G09 1989
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B

SCHEDULE

1b RESTRICTIVE MARKINGS	

3 DISTRIBUTION / AVAILABILITY OF REPORT
Approved for public release; distribution unlimited.

4 PERFORMING ORGANIZATION REPORT NUMBER(S)

5 MONITORING ORGANIZATION REPORT NUMBER(S)
AFOSR·TR· 89-1028

6a. NAME OF PERFORMING ORGANIZATION	6b OFFICE SYMBOL (If applicable)	7a NAME OF MONITORING ORGANIZATION
Indiana University		Air Force Office of Scientific Research/NL

6c. ADDRESS (City, State, and ZIP Code)	7b ADDRESS (City, State, and ZIP Code)
Bloomington, IN 47405	Building 410 Bolling AFB, DC 20332-6448

8a. NAME OF FUNDING / SPONSORING ORGANIZATION	8b OFFICE SYMBOL (If applicable)	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
AFOSR	NL	AFOSR-87-0089

8c. ADDRESS (City, State, and ZIP Code)
Building 410
Bolling AFB, DC 20332-6448

10 SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO
61102F	3484	A4	

11 TITLE (Include Security Classification)

Technical Report: Summary Descriptions of Research

12 PERSONAL AUTHOR(S)
Dr. Charles S. Watson

13a. TYPE OF REPORT	13b TIME COVERED	14 DATE OF REPORT (Year, Month, Day)	15 PAGE COUNT
Annual	FROM 01 Sep 88 TO 30 Jun 89	June 89	56

16 SUPPLEMENTARY NOTATION

17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

During the second year of its URI/AFOSR support, two new psychophysical testing stations have been completed for use in cross-modality sensory and cognitive research. Initial experiments underway with these systems include a visual detection task with auditory cuing and a tactile-visual identificantion experiment. The Institute, by these means, has provided partial support of research leading to the publication, during the past year, of 31 journal articles and book chapters, and the presentation of 30 papers at meetings of scientific societies. The Institute has also supported travel by faculty investigators to Air Force research facilities where they participated in discussions of current research projects. Institute investigators gave a series of research presentations to scientists visiting from Wright-Patterson Air Force Base. (S)

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT	21 ABSTRACT SECURITY CLASSIFICATION
☒ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT ☐ DTIC USERS	UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code)	22c OFFICE SYMBOL
Dr. John F. Tangney	(202) 767-5021	NL

DD FORM 1473, 84 MAR
83 APR edition may be used until exhausted.
All other editions are obsolete.
SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

89 8 08 109

Technical Report

Summary Descriptions of Research
for the period
September 1988 through June 1989

Institute for the Study of Human Capabilities

URI — AFOSR #87-0089

Poplars Research and Conference Center
Indiana University
Bloomington, Indiana 47405

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Annual Technical Report

Summary

This is the second Annual Technical Report of the URI/AFOSR-supported Institute for the Study of Human Capabilities, at Indiana University. The Institute currently consists of eleven affiliated laboratories, in which research is conducted by 16 faculty investigators and a considerably larger number of graduate research assistants, technicians, programmers, and other staff members. One of the primary purposes of the Institute is to provide enhanced opportunities for interactions among these investigators, whose appointments are in six departments (Psychology, Speech and Hearing Sciences, Visual Science, Linguistics, Mathematics, Medical Science) and three schools or colleges (College of Arts and Sciences, School of Optometry, School of Medicine) of the University. Another purpose is to familiarize scientists who are experienced in basic research on sensory processing, cognition, and decision making with current problems in the field of human engineering. Last, the Institute is intended to serve as a source of technical or scientific advice for researchers in government or industry, who are working in areas related to those represented in its laboratories.

We have made significant progress toward these goals, first through the purchase and installation of an inter-laboratory, work-station based computer network. That system has been in operation for the past two years and is now in regular use for the exchange of information and, in several laboratories, for data analysis, graphics, and modeling. Another way that the institute-affiliated faculty interact is by attending institute-sponsored seminars presented by visiting scientists, and through other interactions with these visitors. Funds made available through the institute continue to be used to maintain, repair, and in some cases upgrade research apparatus in the affiliated laboratories. The Institute employs several part-time technicians, programmers, and graduate student research assistants who conduct research under the direction of the faculty investigators. One full-time computer systems administrator has been employed, whose efforts are distributed between support of the inter-laboratory computer network and a research project in color vision.

During the second year of its URI/AFOSR support, two new psychophysical testing stations have been completed for use in cross-modality sensory and cognitive research. Initial experiments underway with these systems include a visual detection task with auditory cuing, and a tactile-visual identification experiment.

The Institute, by these means, has provided partial support of research leading to the publication, during the past year, of 31 journal articles and book chapters, and the presentation of 30 papers at meetings of scientific societies. The Institute has also supported travel by faculty investigators to Air Force research facilities where they participated in discussions of current research projects. Institute investigators gave a series of research presentations to scientists visiting from Wright-Patterson Air Force Base.

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Robert Port, Ph.D.	Associate Professor, Linguistics & Computer Sciences
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| Stephanie Davidson, Ph.D. | Ohio State University | Audiology Laboratory |

The following personnel contributed to research projects described in this report. Those entirely or partially supported by the Institute are identified by asterisks.

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Introduction

This Second Annual Technical Report of the Institute for the Study of Human Capabilities describes work in several areas, all of which focus on problems of skilled human performance. The Institute's investigators are primarily active in the fields of sensory processes including vision, audition, and touch, and in human cognition and decision making; research in those subjects is the major content of this report.

Specific projects examine the abilities of human subjects to use information obtained from visual, auditory, and tactual displays. Both empirical and theoretical studies continue to be conducted. The studies of human cognition include projects on machine-aided detection and recognition, the integration of information from multiple observations, the automatization of decision making, and automatization as a way of overcoming attentional limitations. In hearing, studies include measures of the auditory system's dynamic range, the use of multiple invariant cues in recognition of acoustic signals, pattern discrimination abilities, optimal "packaging" of information in auditory patterns, and discriminability of noise samples. In vision, projects include both theoretical and experimental studies of human color vision. Additional studies examine peripheral vision and the identification of moving stimuli. Studies of the tactual sense include the development of a new tactual stimulator, measures of temporal masking and attention, and the study of higher order processes.

Research Support. All of the research described in this report has been supported either partially or completely by the URI/AFOSR grant to the Institute for the Study of Human Capabilities. It is emphasized, however, that the majority of the investigators also receive project support from other agencies, as listed on pages 50-51 of this report. Institute funds, while a small portion of the total research support of the eleven affiliated laboratories, are the primary reason for the exceptional interdisciplinary cooperation that has developed 'mong its member scientists, during the past two and one-half years. Institute funds have been used, roughly in order of amounts expended to:

(a) design and construct apparatus for cross-disciplinary investigations;

(b) provide supplementary technical assistance for equipment design, maintenance, and computer program development;

(c) support graduate-student research assistants working on Institute-proposed projects;

(d) support visits to the Institute by scientists interested in application of basic research to human engineering problems;

(e) support travel to scientific meetings for the purpose of reporting Institute-supported research; and,

(f) support a one-half time secretary-administrator, and one-third summer salary for the Institute director, C.S. Watson.

Areas of Research. Current research projects in Institute-affiliated laboratorie·, include studies in the following categories:

I   Auditory Discrimination: the psychophysics of auditory capabilities, the limits of auditory attentional capacity, the ability to discriminate signals composed of gaussian noise samples.

II   Tactile Discrimination: development of tactile arrays, and interference in tactile localization.

III   Visual Discrimination: human peripheral vision, human visual optics, spatial processing of color information, perception of moving objects, and color theory.

IV   Bioacoustic Research: sound emission patterns, predictive tracking of moving targets by echolocating bats, ard the physiology of bird song.

V   Cognition and Decision Making: multi-stage decision making, perception of multidimensional complex sounds, differences between visual and memory search, connectionist models for auditory and speech perception, use of fault trees, and computer-based instruction.

VI   Connectionist Models of Sensory and Cognitive Processes: development and testing of neural networks for identification of polysyllabic words and tonal sequences.

Form and content of the reports. It is not our intention to provide sufficient information in the brief project descriptions included here so that any of this work could be replicated. We believe such detail is best reserved for the descriptions of the work that will be submitted to appropriate journals, and specifically discourage any citation of reports which, like these, have not been through the scrutiny of independent peer review. We do hope, however, that the early knowledge of research that is underway or that, because of publication lags, will not appear for some time in the open literature, may be of value to colleagues who are working in closely related areas. We encourage readers of these brief reports to write to individual investigators if further detail is desired on any of the projects. In some instances draft manuscripts are available, and we will do our best to provide whatever information is requested.

New Projects and Personnel. New projects have been begun during the past year in most of the institute-affiliated laboratories, as described in the later section of this report, however two new areas of research deserve special mention. One is the cross-modality research now underway using the recently completed new psychophysical testing stations. Thibos and Bradley are conducting studies of the value of auditory cues in visual search. Craig and Evans (visiting scientist) are investigating observers' abilities to extract coded information from simultaneous or sequential visual and tactile stimuli. Additional cross-modality projects are planned for the third grant year. The other new projects are connectionist models developed by Port, Gasser, and their students. These models successfully recognize isolated polysyllabic words, using only patterns of the duration of individual phonemic components, and brief tonal sequences embedded in an ongoing tonal context. New personnel include one Investigator, Robert Port, who is an associate professor of Linguistics and of computer science, and one associate investigator, Michael Gasser, assistant professor computer science. One Institute-supported visiting scientist, Paul Evans from the University of Washington, is working in the Tactile Laboratory during the summer of 1989, and a second, Theodore Bell from UCLA will be conducting collaborative research in the new Multi-modality Laboratory during academic year 1989-90.

Institute-sponsored Symposium. The Institute will sponsor a symposium on March 21-23, 1990, on "Sensory Processes, Cognition, and Human Engineering." Professor Christopher Wickens, Director of the Aviation Research Laboratory at the University of Illinois, has agreed to serve as co-chairman. The purpose of the symposium will be to review the relation of recent advances in basic research to major applied problems in the field of human engineering. The speakers will include members of the Institute and several investigators from other organizations whose work combines basic and applied research in the field of human perception, cognition, or decision making. The proceedings of this symposium may be published, or possibly be made available as a technical report.

Technical Report Series. The Institute has begun a Technical Report Series, as a means of making research results and theoretical work available prior to publication in journals or elsewhere. In

particular, this series includes the text of papers delivered at scientific meetings (when available), preprints of articles in journals with unusually long publication delays, and certain other reports of more specialized interest than may be appropriate for normal forms of publication. This series is unusual in two ways. First, reports will be circulated *only* in response to requests for specific titles, i.e. *no large-scale circulation is involved, and the text of all reports will be maintained as computer files*, rather than hard copy. Second, copies of reports can be made available through e-mail, when requests are received in that format (excepting reports with complex graphics). Editor of the series is Professor D. E. Robinson. A list of the ISHC Technical Reports will be circulated periodically to the Institute's general mailing list

Reprints. The bibliography at the end of this report lists articles by members of our research groups that have appeared over the past twenty months, a "window" that we will move forward in successive reports.

The design, conduct, and interpretation of experiments in these reports typically reflects the joint intellectual efforts of investigators, research assistants, and many others who participate in the research projects. While we try to give credit where it is due, the ownership of initial ideas is often impossible to establish. We are only certain of who does the work involved in the collection and analyses of data, and who writes the final paper; those persons are formally recognized through authorship, but often a "group as a whole" is as close as we can come to the source of the original ideas for an experiment or for forms of analysis or, most importantly, for a theory. It is a pleasure, at any rate, to work with colleagues who seem to have an inexhaustible reserve of new ways to think about interesting questions.

CSW

Research Project Reports

In general, our rule for inclusion of projects in this report is that they have yielded sufficient new information that we are able to offer a conclusion or two, however tentative those might be. Projects on the drawing board, or so recently underway that no conclusions can yet be proposed, have been reserved for subsequent reports.

1. Auditory Discrimination

1.1 *Proportional target–tone duration as a factor in auditory pattern discrimination.*
Watson, Kidd.

We have recently shown that tonal pattern discrimination is limited not by the number of components in a pattern, but rather by the proportion of the total pattern duration that is subject to change (Watson & Kidd, 1987). Additional experiments were designed to test the limits and generality of the proportion–of–the–total–duration (PTD) rule.

1.1.1 *Do PTD effects vary with the relative durations of individual target and context tones?*

Four ratios of context–tone to target–tone duration (C/T) were tested (.25, .50, 1.00, and 1.50) at each level of target–tone duration and PTD. Total duration and number of components were determined by the combination of target–tone duration, proportion of the total duration, and C/T in each condition.

A strong effect of the target–tone proportion of the total duration was observed for all target–tone durations and C/T ratios. However, the effect of PTD was diminished at the smallest C/T ratio (.25). At this smallest C/T ratio, performance improved much more for PTD = .10 than for PTD = .25, as C/T decreased from .50 to .25. This improvement as C/T decreased from .50 to .25 was the only substantial effect of C/T. This effect tended to diminish as tone durations increased, especially at PTD = .25. Thus, pattern discrimination is primarily determined by the proportional duration of the target components, and is not significantly affected by the ratio of context to target tones, except when the context tones are very brief in duration as well as relative duration.

1.1.2 *Is the PTD effect influenced by changes in target–position uncertainty?*

In our previous PTD experiments, the position of the target tone had always been in the middle temporal position within a pattern. To test the effect of target–position uncertainty, three target locations were used. Target tones could occur at an early (serial position 2) middle (center position) or late (final − 1) position with equal probability. Patterns consisted of 5, 7, or 9 tones with PTD set at .20, .30, or .40. Total pattern duration was fixed at 500 ms. The results showed discrimination primarily dependent on PTD for all positions in spite of the increase in target–position uncertainty. A slightly attenuated PTD effect (primarily for larger numbers of components) was obtained at early and late positions, but this is likely due to the tendency to be more sensitive to changes at these positions (see Watson et al., 1976). The advantage for early and late positions was present when PTD was relatively low (the most difficult discriminations), but was obscured when PTD was increased.

1.1.3 *PTD effects with multiple target tones.*

What remains unclear is whether the improvements in performance with increasing PTD are due to attentional facilitation at a specific location or merely to the increase in the relative amount of

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change in the pattern as a whole. That is, are changes at a particular location more detectable as that tone's PTD increases, or is the change in a pattern property simply more detectable as the proportion of the pattern that is changed increases? One way to resolve this question is to include multiple target tones in nonadjacent positions. Target PTD could then be defined for the set of target tones. If the PTD effect is based on the perception of a holistic pattern property, then the effect of PTD should be unchanged from the single-target case. If, however, the effect is a discrete-tone phenomenon, then performance should be worse than in the single-target case, for a given PTD. This experiment tested the effect of dividing PTD between 2 target tones. The positions of the target tones were always immediately preceding and immediately following the center tone in patterns of 5, 7, or 9 tones. Target PTD values of .20, .30, and .40 were used with total durations of 250, 500, and 1000 ms. Under these conditions the PTD effect was again obtained, with substantial improvements in performance as PTD increased. However, discrimination thresholds for a given PTD were much higher than in the single-target case. If we compare performance with the 500-ms patterns in this 2-target case with the single-target case we see that a PTD of .30 is required to achieve performance comparable to that obtained with a PTD of .40 in the single-target case, and performance at PTD = .40 is inferior to performance at PTD = .30. Thus, it is not simply the proportion of the whole pattern that is changed that determines performance. When PTD is divided between two tones, performance levels are closer to those predicted by the PTD per target tone (i.e., PTD/2 in the present case). The fact that listeners have two chances to detect a target tone probably accounts for the fact that thresholds are slightly lower than obtained for a single target tone at PTD/2.

An additional experiment with variation in the position and separation of two target tones produced very similar results.

These findings are consistent with an attentional-focusing explanation according to which improved resolution for target-tones occupying larger proportions of the total pattern duration is due to facilitation of attentional focusing at the target location. The absolute level of performance, however, is consistent with probabilistic sampling of the two targets (e.g., d' for two equal duration targets is approximately equal to the square root of 2 times d' for one).

1.2 *Detection of changes in frequency- and time-transposed auditory patterns.*
Kidd, Watson.

This series of experiments examined the effect of transposition in frequency and in time on the detection of changes in unfamiliar tonal patterns.

1.2.1 *Frequency- and time-transposition of randomly generated 5-tone patterns.*

In the first experiments, listeners' abilities to detect frequency changes in transpositions of randomly generated five-tone patterns were investigated. A Standard/two-alternative forced choice procedure was used in which a standard pattern was followed by two transposed comparison patterns. One of the comparison patterns was the same as the standard, in terms of the relative frequencies and durations of tones, while the other differed from the standard in the relative frequency of a single tone. Standard patterns consisted of five randomly selected tones, ranging from 300 to 1200 Hz. Total pattern duration was 750 ms. Target-tone duration was set at 30% of the total pattern duration (based on Watson and Kidd, *JASA*, Suppl. 1, 1987) and non-target tones were isochronous. The range of the frequency transposition ratio (i.e., comparison pattern frequencies divided by standard pattern frequencies) was from 1.0 to 2.0 (one octave). The range of the time transposition ratio (time expansion in all cases) was from 1.0 to 3.0. Listeners indicated the different comparison pattern by pressing the appropriate button on a response box. Seven listeners participated in the frequency

transposition experiment and four of those listeners later participated in the time transposition experiment. Both experiments were run for ten 1.5-hour sessions.

Frequency transposition resulted in very large decrements in performance, which occurred with the smallest amount of transposition, with a tendency for additional reduction in performance with increases in the amount of transposition. Average discrimination thresholds for untransposed patterns were around .04 ($\Delta f/f$), increasing to as much as .2 - .3 for even the smallest levels of transposition.

Early in training, time transposition also resulted in a degradation of performance, but to a much lesser extent than frequency transposition. After six hours of training, performance was uniform for all transposition ratios. Individual differences were considerably larger in the time-transposition condition than in the frequency- transposition condition.

These results suggest that listeners have great difficulty using relative frequency information to detect changes in unfamiliar tone patterns. It appears that accurate detection of changes in unfamiliar patterns, in these tasks, is possible only when absolute frequency information can be used.

The situation with time-transposed patterns is quite different. Listeners have some difficulty detecting pattern changes when the total duration of the pattern is altered, but with practice they are able to detect pattern changes quite well, despite large-scale temporal transpositions. Detection of changes in target-tone duration might have been affected more by time transposition. It seems likely that variations in the structure of transposed patterns are generally difficult to detect when they are introduced on the same physical dimension as the transposition. Additional experiments will be conducted to test this hypothesis.

1.2.2 *Frequency transposition with smaller transposition ratios.*

In the frequency-transposition experiment described above, the smallest amount of transposition (a 1.15 frequency ratio) resulted in performance decrements that were nearly as great as the larger transposition intervals. A second experiment was run to determine whether there is a gradual or an abrupt change in performance for smaller transposition intervals. The frequency-transposition experiment was repeated using transposition ratios of 1.00, 1.03, 1.06, 1.09, 1.12, 1.15 (i.e., five log steps from 1.0 to the smallest interval used in the previous experiment). Performance was found to decrease gradually over this range for all but one of the four subjects who showed a rather abrupt decrease in performance.

1.2.3 *Transposition with reduced uncertainty.*

To test the extent to which transposition performance is adversely affected by transposition uncertainty (i.e., uncertainty with respect to the amount of transposition on a given trial), the frequency- transposition experiment was run again with a single transposition ratio (1.52). Even after 10 hours of practice at this transposition ratio, little or no improvement in performance was obtained. Considerable trial-to-trial stimulus variation remained in this experiment, however, and may be responsible for some of the poor performance.

1.2.4 *Interval transposition.*

A related line of investigation has been started using two-tone patterns (i.e., single frequency intervals). These experiments are designed to provide a more direct test of the basic ability to detect changes in relative frequency by using the simplest possible stimuli required to test this ability. The

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procedure was the same as in the five-tone transposition experiments with frequency changes introduced on the second tone of the pair. Interval sizes of 3.0, 3.5, 4.0, and 4.5 semitones were tested. The narrower range of transposition ratios was used in initial investigations.

For positive interval changes (i.e., frequency increases for the altered tone) performance was similar to that with five-tone patterns. Threshold values of $\Delta f/f$ ranged from around .02 to .05 for untransposed intervals and increased to around .1 or greater at the 1.15 transposition ratio. There was also a consistent tendency for thresholds to increase as the size of the interval increased, with no indication of better performance with transposition equal to even numbers of semitones.

For negative interval changes, the effect of transposition was quite different. Performance tended to improve with increasing amounts of transposition, with best performance associated with the largest interval sizes. However, the detection of negative interval changes was generally poorer for all transposition levels, than the detection of positive interval changes. This dependence of the effect of transposition on the direction of the interval change appears to be due in part to confusion about whether and how much the interval has been transposed on a given trial. In other words, trial-to-trial stimulus uncertainty continues to be a likely cause of the very poor performance in these transposition experiments, even for two-tone patterns. Minimal uncertainty versions of these experiments are therefore being prepared.

In an additional experiment with a wider range of transposition intervals (2, 4, 6, 8, and 10 semitones), thresholds decreased with increasing amounts of transposition for both positive and negative interval changes, although this was more pronounced with negative interval changes. Additional transposition experiments are being conducted using other psychophysical procedures.

1.3 *Development of norms and factor analysis of TBAC performance obtained in 398 listeners*
Espinoza-Varas, Watson

Since first developed (Watson et al., *J. Acoust. Soc. Am.* 1982, 71, S73), the eight-subset Test of Basic Auditory Capabilities (TBAC) has been administered to approximately 600 listeners, in 10 different studies carried out at the Boys Town National Institute, the University of Nebraska, Lincoln, University of Wisconsin, Madison, and the Speech and Hearing Center, Indiana University. This large data base offers a unique opportunity to standardize and develop norms for the TBAC and to perform factor and cluster analyses. We have recently consolidated the data from the various studies, which were previously stored in several different formats and media. We have developed a coherent structure for this data base and currently have TBAC results for 398 listeners entered in the CDC-856 Indiana University computer, which has available appropriate statistical packages. Preliminary analyses have confirmed that the TBAC is a reliable test, that the three-factor partitioning of the variance on the TBAC is a stable result, and that performance on these tests has an unexpectedly strong association with certain intellectual measures (WAIS scores, SAT's).

1.4 *Detection thresholds for isolated vowels.*
Kewley-Port

A series of experiments on the detectability of vowels in isolation has been completed. Stimuli consisted of three sets of 10 vowels, one synthetic, one from a male talker and one from a female talker. Vowel durations ranged from 20 to 160 msec. Thresholds for detecting the vowels in isolation were obtained from well-trained, normal-hearing listeners using an adaptive-tracking paradigm. Detection thresholds for vowels calibrated for equal sound pressure at the earphones differed by as much as 20 dB across vowels. However, the same patterns of thresholds obtained for the vowel set were obtained for all vowel durations. An orderly decrease in vowel thresholds was obtained for

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increased duration, as predicted from temporal integration for pure tones. Several different analyses have been conducted in an attempt to explain the differential detectability for the various vowels within each set. The most detailed of these analyses involved a model developed by Moore and Glasberg (1987) for calculating excitation patterns and the corresponding loudness level in phons. Although that model provided improved explanatory power over other models examined, further refinements of perceptual models of loudness will be needed to explain these data.

1.5 *Modulation Transfer Functions*
Humes

We have been interested in the applications of acoustical and psychoacoustical modulation transfer functions (MTFs) as predictors of speech-recognition performance in normal and hearing-impaired listeners. Since the last report, several experiments have been completed in these areas. The work with acoustical MTFs has focused on evaluation of the modified Speech Transmission Index (mSTI). The mSTI is an index derived from measurement of acoustical MTFs and is monotonically related to speech-recognition performance in normal listeners. Two experiments in this area are summarized below.

1.6 *Application of the modified Speech Transmission Index to the Speech Recognition of Normal and Impaired Listeners Wearing Hearing Protection.*
Humes, Wilde

The present study examined the application of the modified Speech Transmission Index (mSTI) as a predictor of the speech- recognition performance of normal and hearing-impaired listeners, with and without hearing protection. The speech-recognition scores of twelve normal and twelve hearing-impaired subjects were measured for a wide range of conditions designed to be representative of those in the workplace. Conditions included testing in quiet, in two types of background noise (white vs. speech-spectrum), at three signal-to-noise ratios (+5, 0, -5 dB), and in three conditions of protection (unprotected, earplugs, earmuffs). The mean results for all twenty-one listening conditions and both groups of subjects were accurately described by the mSTI. Moreover, a single transfer-function relating performance to the mSTI could describe all of the data from both groups.

1.7 *Application of the Modified Speech Transmission Index to Monaural and Binaural Speech Recognition in Normal and Impaired Listeners.*
Humes, Roberts.

In this study, acoustical modulation transfer functions were measured in anechoic and reverberant environments. In both environments, measurements were obtained in quiet and in two different noise conditions; noise at 0° azimuth and at 90° (R) azimuth. The speech source was always located at 0° azimuth. Measurements were made using both an omni-directional microphone in the sound field and microphones located at the right and left "ear drums" of a special manikin used for acoustic research (KEMAR). Following the acoustical MTF measurements and the calculation of the modified Speech Transmission Index (mSTI) from these measurements, a standardized recording of nonsense syllables was played and recorded through the microphones of the manikin under the same acoustic conditions. The nonsense syllables were later presented over headphones to a group of 13 young normal listeners and the percent of nonsense syllables recognized correctly was established for each acoustical environment. Scores were obtained for materials presented to each ear separately (monaurally) and to both ears (binaurally). Results from the normal listeners are accurately described by the mSTI. As the mSTI increases, the number of nonsense syllables recognized correctly also increases. A single function relating percent correct to the mSTI provided an accurate description of the data for both monaural and binaural listening conditions when the best-ear mSTI values were

used for the binaural conditions. This suggests that potential improvements in speech-recognition in noise associated with binaural-interaction (release from masking, squelch) may not be necessary to consider in calculation of the mSTI for binaural conditions, as long as ear-specific mSTI values are available. Groups of listeners having sensorineural hearing loss are currently being tested.

Work has also been completed on the measurement of psychophysical MTFs for measurement paradigms that parallel the acoustical measurements. In the acoustical measurements, the MTF represents the amount of modulation that has been preserved by the system under study for an input signal consisting of a 100% intensity-modulated noise. Most of the psychophysical MTFs that have been reported previously, however, measured the minimum detectable amount of modulation as a function of modulation frequency. A few studies that have measured the preservation of modulation with paradigms using 100% amplitude-modulated noise have reported psychophysical MTFs that differ from those obtained with the modulation-detection paradigm. In the following experiment, we evaluated three methods of measuring psychophysical MTFs; two that measure the preservation of maximum modulation and one that measures the minimum detectable amount of modulation. A second experiment is then described in which the preservation of maximum modulation was measured in normal, noise-masked normal and hearing- impaired listeners.

1.8 *Psychophysical Modulation Transfer Functions: A Comparison of the Results of Three Methods.*
Scott, Humes

Modulation transfer functions were measured and compared for three different psychoacoustical paradigms in the same normal- hearing subjects. The three methods are referred to as the temporal-probe method, the derived-MTF paradigm, and the modulation-detection method. In the temporal-probe method, the threshold of a 4-ms probe tone (at either 1000 or 4000 Hz) was measured at various envelope phases within a 100% sinusoidally amplitude-modulated noise at modulation frequencies from 2 through 256 Hz. For the derived-MTF method, the threshold of a 500-ms tone at 1000 and 4000 Hz was measured in the same noise at the same modulation frequencies. For the modulation-detection paradigm, just-detectable modulation was measured, as a function of modulation frequency, for SAM noise that was bandpass filtered and centered at 1000 and 4000 Hz. MTFs with lowpass shapes were observed with all three methods. Differences were observed in the cutoff frequencies and/or attenuation rates when the data were fitted mathematically with lowpass filter transfer functions. The various methods do not appear to converge to identical MTFs.

1.9 *Masking of Tone Bursts by Modulated Noise in Normal, Noise-Masked Normal and Hearing-Impaired Listeners.*
Humes

Threshold for 4.6-ms tone bursts was measured in quiet and in the presence of a 100% sinusoidally amplitude-modulated speech- shaped noise. For the modulated-noise conditions, the onset of the tone burst coincided either with the maximum or the minimum modulator amplitude. The difference in these two masked thresholds provided an indication of the psychoacoustic modulation depth, or the modulation depth preserved within the auditory system. Modulation frequencies spanning the modulation spectrum of speech (2.5 to 20 Hz) were examined. Tone bursts were 500, 1400 and 4000 Hz. Subjects included normal listeners, normal listeners with a hearing loss simulated by high-pass noise, and hearing-impaired listeners having high-frequency sensorineural hearing loss. Normal listeners revealed a psychoacoustic modulation depth of 30-40 dB for the lowest modulation frequencies which decreased to about 15 dB at 20 Hz. The psychoacoustic modulation depth was decreased in the normal listeners with simulated hearing loss and in the hearing-impaired listeners. There was general agreement in the data, however, for the latter two groups of listeners

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suggesting that the normal listeners with a hearing loss simulated by an additional masking noise provided a good representation of the performance of hearing–impaired listeners on this task.

1.10 *Modeling Masking and Loudness*
Humes, Jesteadt

In a series of papers, we have described a model of masking additivity (Humes and Jesteadt, 1989) and the application of that model to sensorineural hearing loss (Humes, Espinoza–Varas and Watson, 1988). The model is based on a nonlinear transform relating measured masked thresholds to underlying internal effects. The transform, referred to as the "modified power law with compressed internal noise," by Humes and Jesteadt (1989), has the following general form:

$$i_x = I_{MTx}{}^P - I_{QT}{}^P$$

where i_x represents the internal effect produced by masker x at the signal frequency, I_{MTx} is the

intensity of the signal at masked threshold for masker x, I_{QT} is the intensity corresponding to quiet threshold at the signal frequency, and P is a value ranging from 0.0 to 1.0. When applied to the additivity of masking for two maskers, a and b, simple additivity of *internal* effects was assumed;

that is, $i_{ab} = i_a + i_b$. Humes and Jesteadt (1989) found the best–fitting P–values of the model ranged from 0.1 to 0.4 for most studies of masking additivity. In modeling sensorineural hearing loss, Humes et al. (1988) set P=0.3 and found good agreement between the data and the model for many measures of frequency resolution.

The present work extends the previous modeling of masking additivity in normal and impaired listeners to measures of loudness. Areas being examined include loudness growth, additivity of loudness and binaural summation of loudness. It has been demonstrated that the same model, the modified power–law model with compressed internal noise, provides a good description of these data from normal and impaired listeners. This is accomplished, moreover, by setting the model parameter, P, to values between 0.1 and 0.4 for all measures.

In addition, in the area of masking, we have demonstrated that the model provides a good approximation of the performance of listeners with sensorineural hearing loss for measures of masking produced by modulated noise (Humes, in press; see summary above) and for the perception of second–formant transitions (Ochs et al., 1989). Work is ongoing to evaluate the model for a variety of psychoacoustic measures including intensity discrimination, frequency discrimination, duration discrimination, and temporal order.

1.11 *Multiple Targets: Detection and identification of auditory signals in noise*
Robinson, Rickert

The multiple target problem, and the consequent requirement for target categorization, has been simplified to the case of equally detectable, orthogonal signals. The set of potential signals used in this experiment consisted of four sinusoids (500, 1100, 1900, and 2700 Hz). In order to satisfy the condition of equal detectability across channels, the signal–to–noise ratio for each the four frequencies was adjusted to achieve a P(C) of approximately 0.75. We assumed that the wide frequency separation between signals was sufficient to meet the condition of orthogonality. That is, each signal

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frequency is processed independently. These assumptions allow application of a theorem relating target detection and identification (Starr, Metz, Lusted, and Goodenough, 1975). In a combined detection–identification task, subjects were asked to listen during a specified observation interval and to make two decisions: (1) report the presence or absence of a tonal signal in a broad–band gated noise, and (2) indicate which one of the four signals occurred. The overall a priori probability of signal–plus–noise and noise–alone trials was balanced at 0.50. Further, each of the four frequencies was equally likely to occur on a signal–plus–noise trial. Group mean data indicate that detection performance exceeds identification performance by approximately 14 percent (0.77 to 0.63). Although more elaborate analyses are required to evaluate statistical fit to the data, the predictions made by the theorem are consistent with observed performance.

1.12 *Effect of changing the distribution of targets over channels*
Robinson, Rickert

We have completed a pilot study to investigate the effects of changing target probability over channels within the detection–recognition task. The experimental procedures described in the previous section were also used in this study. The a priori probability of a signal occurring was maintained at 0.50. However, on signal trials the probability of the 500 Hz signal was reduced to 0.10 while the probability of the remaining signals was increased to 0.30. Preliminary results indicate that identification performance increases relative to identification performance when the a priori probabilities of the four signals are equal.

1.13 *Molecular Psychophysics*
Robinson, Fallon

In their work concerning the role of stimulus uncertainty in the discrimination of complex tonal patterns, Watson, Kelly and Wroton (1976) and Watson and Kelly (1981) distinguish between central and peripheral factors that limit the processing of sensory information. They argue that the limits on information processing that can modified by manipulating stimulus uncertainty (i.e., smaller set size, over–training, etc.) are central, whereas those that cannot be modified are peripheral. The main goal of the research described here is to determine whether the discriminability of different 'target' segments (i.e., beginning, middle, and end) within a random, time–varying waveform can be altered by minimizing stimulus uncertainty.

Previously, we have used free–running samples of noise such that new waveforms were generated prior to each trial. This method made it impossible for subjects' to base their decisions on long–term information about the spectral–temporal characteristics of the noise samples. If, however, the factors affecting discriminability of deterministic tonal sequences and stochastic waveforms are similar, then it may be possible to eliminate the effects of temporal position by (1) reducing the size of the stimulus set from which samples are drawn and by (2) over–training.

Two separate experiments, both employing a two–interval, same–different method were conducted. All stimuli used were samples of computer–generated broad–band Gaussian noise, 150 msec in total duration. The first experiment was designed to estimate the hit and false alarm rates for each of twenty 'Same' pairs and twenty 'Different' pairs. This experiment measured subjects' relative performance for each of the individual samples. The data indicate that all pairs of noise samples are not equally discriminable. There is considerable scatter when the points are plotted in ROC space. Although these samples have identical long–term statistical properties, it is likely that the observed variability among samples is due to differences in their short–term power or energy spectra. Thus some pairs of noise samples are more discriminable than others. A subset of these samples was then used in the second experiment. The samples which were selected were chosen to maximize their separation in ROC space. In this experiment only two noise bursts (one 'Same' and one 'Different')

were run in each experimental block. Moreover, the same noise bursts were used in successive blocks. Several experimental sessions were conducted for each pair of noise bursts in order to monitor changes in discrimination performance that might have resulted from over–training. We were unable to find evidence for improved performance with this reduced stimulus set and a large number of trials.

1.14 *Dichotic Presentations*
Robinson, Rickert

Several binaural phenomena (e.g., the precedence effect) suggest that interaural differences occurring at the beginning of an acoustic event should be more effective cues than those occurring later. In the context of our previous work concerning the discriminability of diotic samples, these phenomena suggest that the advantage of the 'end' condition might not be found with dichotic presentations. Thus, the main goal of extending our research to include binaural listening tasks has been to determine whether the factors affecting performance for diotic presentations act in a similar fashion when there are interaural differences. Using a single–interval, yes–no procedure we asked listeners to detect the presence of an interaurally uncorrelated segment of noise within an otherwise diotic waveform. Psychometric functions were obtained for three overall durations (25, 75, and 150 msec) by systematically varying two stimulus parameters: (1) the duration of an interaurally uncorrelated segment of noise, and (2) the temporal position of the uncorrelated segment within the noise burst. All noise samples used were broad–band Gaussian with spectral density equal to 50 dB SPL/Hz. The data indicate (1) that independent of overall sample duration, detection improves as the duration of uncorrelated noise is increased, and (2) that for a fixed duration of uncorrelated noise, performance depends on temporal position. In general, segments positioned at the end of a noise burst are more detectable than those positioned either in the middle or at the beginning of the burst. These results pose an interesting theoretical challenge for at least one current model of binaural signal processing. Since the equalization–cancellation model (Durlach, 1963) assumes that the quantity used as a decision statistic is computed over the entire stimulus duration, it is unable to account for the observed effects of temporal position on the detectability of an interaurally uncorrelated segment of noise.

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2. Tactile Discrimination

2.1 *Processing Tactile Patterns at Several Locations*
Craig

In perceiving tactile patterns, it has been argued that the fingerpads are the "retina" of the skin. This argument has been supported by anatomical and neurophysiological investigations (high density of innervation, large cortical magnification) and by psychophysical studies (high spatial acuity). Hence, the choice for presenting complex spatial/temporal patterns has been the fingerpads. There is an obvious drawback to occupying the fingers with the tactile displays necessary to generate such patterns: the fingers are often occupied with other sensory and motor tasks. Few investigations have, however, compared directly pattern processing at the fingerpads with other locations. During the course of a study of tactile speech aids, such a comparison was carried out.

The two sites of stimulation were the left index fingerpad and the left forearm. Speech signals were analyzed by means of a principle component analysis. This program generates a number of "components" of the speech waveform. Two of these components were selected and displayed on two- dimensional tactile arrays. One array was the 6 by 24 display from the Optacon, a reading aid for the blind. This display presents two-dimensional patterns, such as letters, to the user's left index fingerpad. The second array was developed in our laboratory and consists of 30 tactile stimulators, arranged in a 6 column by 5 row configuration, that can be worn on a subject's arm.

Several sets of speech signals were analyzed and presented to subjects one at a time. The subject attempted to identify the speech signal and received trial-by-trial feedback. Sessions alternated between testing the forearm display and testing the finger display. Sets of consonants and vowels were tested. The results showed no advantage for the fingerpad display. Indeed, as measured both by percent correct and by the amount of information transmitted, the forearm display was slightly superior to the fingerpad display.

The results suggest that subjects may be able to extract pattern "invariances" regardless of the site to which patterns are presented. The applied implications of the result are that designers of tactile displays should not immediately assume that the fingerpads should be the site of choice. Other sites should be examined, particularly if occupying the hands with a tactile display is a problem. This work is currently being written up as part of a larger project with Janet Weisenberger, Gray Abbott, and Xu Baihua. (Weisenberger, J., Craig, J.C., & Abbott, G. Evolution and evaluation of a principal-components tactile aid for the hearing-impaired. In preparation.)

2.2 *Multi-Modal Pattern Processing.*
Evans and Craig

With the development of the multi-modal test facility, we have begun to investigate correspondences that may exist between the processing of spatial patterns presented visually and tactually. The starting point for the current research is the finding by Posner and Keele (1967) that when asked to determine if two visually presented letters share the same name, subjects are faster at making such responses when the two letters are physically identical (for example, A - A) than when they are different (for example, A - a). The advantage for physically identical pairs holds when the two patterns are presented simultaneously and decreases as the temporal separation between the onsets of the two patterns is increased. On the basis of this, and related findings, Posner and Keele (1967) concluded that visually presented letters are initially encoded in terms of a spatial code enabling a fast "same-name" response when the two stimuli match physically. The fact that the

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advantage of physically identical stimuli decreases steadily with increases in the interstimulus interval (ISI) suggests that the amount of spatial information declines steadily until both letters share a common, perhaps verbal, code.

We replicated the original experiment conducted by Posner and Keele (1967) and obtained very similar results. Subjects were presented with one of five letters (A, E, H, L, T) on a visual display followed by a second letter that was either in upper- or lower-case. The subjects' task was to indicate, as quickly as possible, whether the two letters shared the same name. The second letter was presented simultaneously with the first, or followed the first letter after a variable ISI (500, 1000, or 1500 msec). When the two stimuli were presented simultaneously, there was an advantage for physically identical letter pairs of approximately 70 msec. This advantage decreased with increasing ISI. In brief, the results were very similar to those reported by Posner and Keele (1967).

To investigate whether spatial tactile letter are initially processed in a fashion similar to that of spatial visual letters, we recently conducted a cross-modal variation of the same-different discrimination task described above. Subjects were presented with two letters. One of the letters was presented tactually using the tactile array of the Optacon. The other letter was presented visually using a high-resolution display. The two stimuli were presented either simultaneously, or the visual stimulus followed the tactile stimulus by one of four different ISIs (100, 500, 1000, or 1500 msec). The tactile stimulus was always uppercase (A, E, H, L, T). Prior to their participation in the study, all subjects had received extensive practice in identifying these patterns. The visual stimulus was either upper- or lower-case. The subjects' task was to indicate, as quickly as possible, whether the two patterns shared the same name.

If tactually presented letters are initially encoded in a fashion similar to that of visually presented letters, that is, in terms of their spatial characteristics, then we might expect physical identity matches to be faster than matches that must be based solely on the names of the patterns. When the tactile and visual stimuli were presented simultaneously, or when the visual stimulus was presented 100 msec after the onset of the tactile stimulus, a relatively large reaction-time advantage (approximately 70 msec) was obtained when the two stimuli were physically identical. With an ISI of 500 msec or greater, the difference between the physical identity and name identity responses was relatively small. The results suggest that tactually presented letters are initially encoded in terms of a spatial code and that this code decays with time. However, even at the longest ISI, 1500 msec, 4 out of 5 subjects showed a slight, approximately 20 msec, advantage for physically identical letter pairs. This result is consistent with previous results that suggest that a veridical representation of a tactile pattern persists for durations greater than one second.

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3. Visual Discrimination

3.1 Human Vision

3.1.1 *Contrast Sensitivity of the Peripheral Visual System.*
Thibos, Bradley, Still.

In central vision, patterns too fine to be resolved appear to lose contrast and so become indistinguishable from a uniform, blank field. We have shown that quite the opposite occurs for peripheral vision. Patterns are easily detected as high-contrast "aliases" even when the stimulus is much too fine to be resolved. We have measured visual sensitivity to such "supra-resolution" targets and have found that it can be as much as an order of magnitude above absolute threshold. For example, at 30 deg in the periphery, contrast sensitivity is about 10 at the resolution limit of 3 cyc/deg. Contrast sensitivity does not fall to the absolute threshold of unity until spatial frequency is increased to about 20 cyc/deg. Overall, the shape of the contrast sensitivity function at the 30 deg locus is that of a bandpass filter which peaks at about 1.5 cyc/deg and which passes smoothly through the limiting frequency for resolution.

3.1.2 *Chromostereopsis.*
Ye, Zhang, Bradley, Thibos.

Chromostereopsis is a visual illusion of depth observed for targets of different colors thought to be caused by chromatic aberration of the eye. Using detailed measurements of monocular transverse chromatic aberrations, we have been able to predict the direction and magnitude of chromostereopsis. For small pupils (e.g. 1mm diameter) monocular visual direction is optically determined as shown by chiefray analysis. Similarly, interocular differences in visual direction for different wavelengths accurately predict the amount of binocular disparity underlying chromostereopsis. Using concentrically dilating artificial pupils (1–7mm) we have experimentally demonstrated chromostereopsis for larger pupils. These results indicate a second factor becomes operative: retinal directionality (i.e. the Stiles–Crawford effect). Incorporation of the SC-effect into the optical calculations then accounts for the entire range of data for all pupil diameters.

3.1.3 *Color vision.*
Bradley, Zhang, Thibos

A widely used method for studying the spatial properties of color vision employs patterns that have no luminance gradients. These "iso-luminance" patterns are made up entirely of variations of hue or saturation and therefore isolate the color system for study. One potentially serious limitation of the method is that the chromatic aberration of the eye will introduce luminance artifacts into the retinal image, thus upsetting the crucial iso-luminance balance. We have calculated the magnitude of this artifact using our model of chromatic aberration of the human eye and have found it can be sizable. For example, 100% color modulated grating displayed with the red and blue phosphors of a typical color monitor is 23% at 10 cyc/deg, well above detection threshold. In the laboratory setting, the artifact is exacerbated by the use of various devices designed to correct ocular chromatic aberration, such as achromatizing lens or artificial pupils. When chromatic difference of focus is corrected, displacement of the achromatizing lens by just 0.5 mm is sufficient to produce a supra-threshold luminance artifact. Using closed-circuit TV we have monitored head movement when the head is unrestrained and when using a bite bar. With free movement, the artifact of chromatic aberration is so large it defeats most useful experimentation. Even when employing a bite bar, small residual head movements are sufficient to limit the use of iso-luminant stimuli to low spatial frequencies.

3.2 Human Visual Optics

3.2.1 *Theory of ocular chromatic aberration.*
Thibos, Bradley, Zhang, Still, and Howarth.

Despite its importance for understanding the optical limitations to visual performance, no quantitative model of ocular chromatic aberration is available. To fill this gap, we are devising a simple, yet realistic, model capable of making explicit, quantitative predictions suitable for experimental testing. The resulting theoretical development has provided for the first time a unified treatment of both the transverse and longitudinal components of ocular chromatic aberration. Experimental verification of the model has progressed on two fronts. First, using natural vision through an artificial pupil, we have measured the magnitude of transverse chromatic aberration and have found it to be equal to 4 arcmin/mm of displacement of the artificial pupil. For peripheral vision, this corresponds to 0.25 arcmin/deg of visual eccentricity. Essentially the same results were obtained independently by a second method using an interferometric visual stimulator. One unexpected fact which emerged from these experiments is that although the eye has substantial chromatic aberration, the natural pupil is well centered on the visual axis, thereby minimizing the transverse component of chromatic aberration and so optimizing foveal image quality for polychromatic objects.

3.2.2 *Image quality in peripheral vision.*
Still, Thibos, Bradley.

Previous attempts to measure optical image quality in the peripheral visual field have been thwarted by the poor spatial acuity of the peripheral retina. For example, at 30 deg eccentricity patterns are resolvable only if they lie in the range 0-3 cyc/deg, a range of frequencies too low to be significantly limited by optical factors. In order to gain access to the crucial range of higher spatial frequencies, we have taken advantage of our recent discovery that patterns beyond the resolution limit are still visible as illusory percepts called "aliases." Optical modulation transfer functions were obtained as the ratio of contrast sensitivity for grating detection measured under two conditions. First, the retinal image was formed with a monochromatic interferometer to avoid the defocusing effects of optical aberrations of the eye. The experiment was repeated for natural viewing (5mm pupil) of gratings displayed on an oscilloscope. Refractive errors were carefully determined and corrected with spectacle lenses. By assuming the retinal contrasts for any given spatial frequency were identical under the two conditions, the ratio of stimulus contrasts is a measure of the contrast attenuation caused by the eye's optical apparatus. The results indicate that optical image quality for peripheral viewing is nearly as good as for central viewing measured in the same way.

3.2.3 *Applied optics.*
Thibos.

The widely used interferometric method for bypassing the optics of the eye was first described over 50 years ago but has never been shown to be immune to the effects of ocular chromatic aberration. Our experiments have indicated that the polychromatic interferometer is likely to suffer markedly from chromatic aberration of the eye. To show the physical basis for this effect, the operation of the interferometer in conjunction with the human eye was investigated theoretically. It was shown that if the interferometer is misaligned with the visual axis of the eye then the prismatic effect of transverse chromatic aberration causes wavelength-dependent phase shifts in retinal fringes. This shift is directly proportional to the magnitude of the longitudinal chromatic aberration of the eye. The net effect is a significant loss of retinal contrast for polychromatic fringes which can lead to threefold loss of visual acuity.

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3.3 Color Theory

3.3.1 *Nonlinear Gain Control Models of Visual Adaptation and Color Perception*
Guth

Continuing work has involved theoretical explorations of the model that was developed during the first two years of the project. The model attempts to account for the major data in the fields of visual adaptation and color perception. This approach differs from the common strategy of limiting theoretical and experimental work to a very narrow data set. Too often in visual psychophysics, theorists seem to forget that every property that is assumed to hold for one aspect of visual processing must have implications for all others.

For example, suppose that a researcher, who is interested in light adaptation (rather than color vision) suggests that a particular set of data can be accounted for using a model that includes a neural compression stage that operates on neural signals late in the visual pathway. If such a mechanism exists, then it must be important in understanding color vision, for chromatic stimuli are processed by mechanisms that mediate the perception of white light as well as by chromatic mechanisms. At the very least, the hypothesis has direct implications for data concerning (i) the apparent saturations of chromatic lights at various luminances, (ii) the effects on color appearances of adding white lights to chromatic lights, (iii) intensity discriminations for chromatic lights flashed on white backgrounds, (iv) intensity discriminations for chromatic lights flashed on chromatic backgrounds, and (v) apparent brightnesses of white-plus-chromatic light mixtures. Conversely, hypotheses about color vision should be tested to determine their implications for the perceptions of white lights.

The model that has already been developed includes processing stages that are, for the most part, not controversial. The first stage includes the cone receptors whose outputs are assumed to include noise. A second stage is a gain control mechanism that attenuates receptor (and noise) signals. The third stage consists of opponent and nonopponent mechanisms that mediate chromatic and achromatic percepts in accordance with now classical ideas. The fourth stage compresses neural activity from the third stage mechanism, and the fifth (final) stage combines the compressed signals from the opponent and nonopponent mechanisms in accordance with a vector summation rule. (The only controversial stage of the model is the vector summation stage. The evidence that has been presented to discredit vector summation is, we argue, only meaningful within linear theory, has been generally rejected.) The most innovative aspect of the model is the particular form of the receptor-gain-control rule, and it is mainly this gain control rule that allows the model to account for many results that have not previously been explained by any theory.

Among the phenomena that the model is the first to successfully describe are:

(i) All of the poorly-understood hue shifts that are associated with changing saturations and luminances of chromatic lights. (These are called Munsell shifts, Abney shifts and Bezold-Bruecke Shifts.)

(ii) An almost perfect (given data uncertainties) account of MacAdam's ellipses.

(iii) An account of very unusual data that indicate that violet-plus-white mixtures are brighter than expected from linear additivity theory, whereas green-plus-white and red-plus white mixtures are dimmer than expected.

(iv) An excellent account of very complex data from Stiles that show increment thresholds for various monochromatic lights flashed on various chormaticbackgrounds of varying luminances. These predictions are particularly impressive, because they require that the model be capable of predicting not only Weber's law (which holds approximately when increment andbackground are the same wavelength) but also gross departures from Weber's law (which occur when increment and background wavelengths differsubstantially.

(v) An unexpected account of the effects of chromatic adaptation on color matches and color appearances. The account is unexpected, because the model was not developed with these data in mind, and further, these data have historically been thought to demonstrate that receptor gain controleffects could not account for chromatic adaptation phenomena.

Although the model can explain the above data, as well as many other results, it is not without its problems. For example, most discrimination data can be best predicted with a particular set of receptor-to-opponent mechanism connections, whereas color appearance data can best be accounted for with a different set of connections. The past year has been spent exploring a very large number of model variations in an effort to solve the remaining problems, but without introducing new parameters. That is, the working strategy has been to avoid using different parameters for each receptor type and for each post-receptor mechanism.

In summary, the search for a model that describes all major data in the field has already provided worthwhile new insights about the mechanisms and mathematical functions that underlie visual adaptation and color perception, but much additional work remains.

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4. Bioacoustic Research

4.1 Vocal Tract Acoustics of Echolocating Bats

4.1.1 *Vocal tract acoustics of the mustached bat.*
Suthers, Hartley, D. J.

Parnell's mustached bat, *Pteronotus parnellii*, is an interesting and intensively–studied New World species that hunts for insects in spatially cluttered environments. The Old World horseshoe bats (*Rhinolophidae*) occupy a similar ecological niche, and have a number of echolocation system characteristics in common with the mustached bat. Among these are the use of long, constant–frequency pulses with a "missing" fundamental and unusual modifications of the trachea posterior to the larynx. In the mustached bat, the tracheal modification takes the form of an elastic portion of the trachea that becomes inflated during vocalization. With the aim of further exploring this example of convergent evolution in echolocation systems, we investigated the functional anatomy of the mustached bat vocal tract to see how it compared with what is known about the horseshoe bat vocal tract. First, we used light and heavy gases to obtain the vocal tract transfer function (Fig. 1, see next page) and then used this information to look for the anatomical basis of fundamental filtering. We found that fundamental attenuation is probably due to a combination of phase–shifted reflections from the nasal passages and an area–function filter. Second, we prevented inflation of the tracheal sac and observed the effect of this treatment on tracheal sound in light and heavy gas atmospheres. The results suggest that the tracheal sac reflects sound back to the larynx to improve vocal efficiency, but are not conclusive.

4.1.2 *Radiation pattern of the mustached bat sonar pulse.*
Suthers, Hartley, D. J.

We obtained the radiation pattern for the mustached bat and compared it with various model sources. At the second and third harmonic, sound radiation is highly directional and consistent with the idea that the mouth acts as a conical horn.

4.2 Behavioral Measures of Animal Sonar Performance

4.2.1 *Acoustic behavior of the fishing bat (Noctilio leporinus) during prey capture.*
Suthers, D.J. Hartley, K.A. Campbell

Many bats change the acoustic parameters of their echolocation pulses in a deliberate manner during prey capture. Attempts to quantify these changes, have been either of limited scope or subject to potentially severe errors due to an inadequate consideration of the directionality of both the bat and the recording microphone. We have therefore recorded the echolocation pulses emitted by *N. leporinus*, as it approaches and catches stationary food, with the microphone positioned in such a way that the structure of the pulses actually incident upon the target can be accurately determined. Analysis of these recordings shows that:

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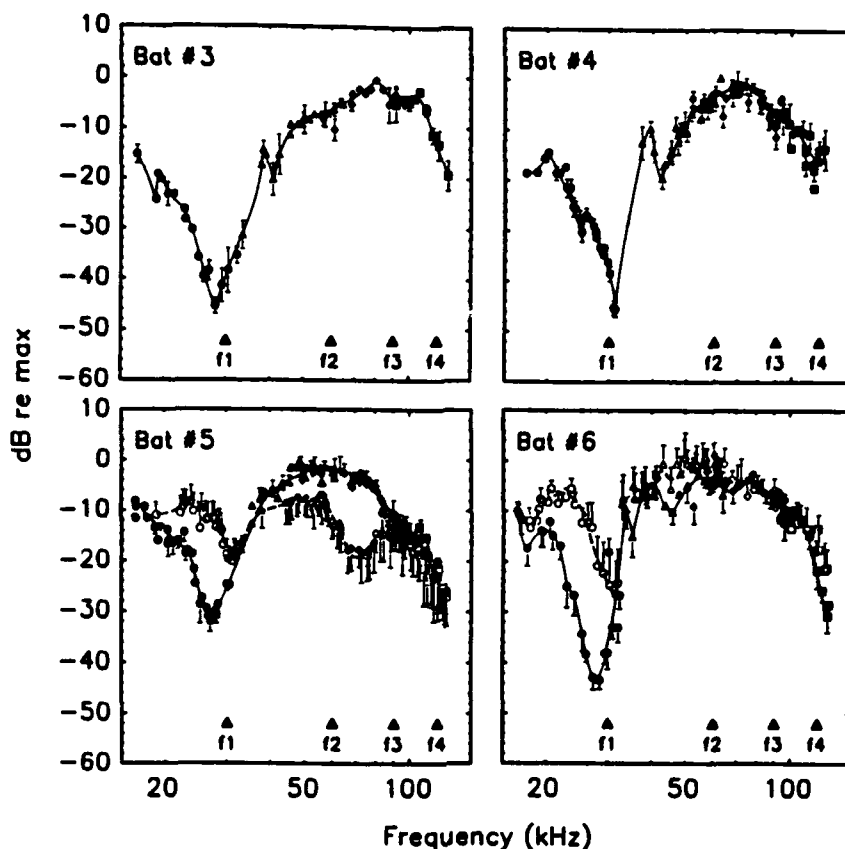
Figure 1. Transfer functions for four individual bats. Upper plots show transfer functions for bats with an intact vocal tract. Lower plots show transfer functions before (solid symbols, unbroken line) and after (open symbols, broken line) partial filling of the nasopharynx. The transfer functions for the intact condition are normalized relative to the maximum value; those after nasopharyngeal filling are normalized relative to the maximum value of the intact transfer function for that individual. Plot symbols in this and subsequent figures are mean with standard deviation for pulse components f1 (circles), f2 (triangles), f3 (diamonds) and f4 (squares). Postmortems as follows. Bat #5: the nasopharynx was completely filled and hence the nasal passage was also completely blocked. Bat #6: the nasopharynx was only partially filled (about 25%) but the nasal passage was completely blocked.
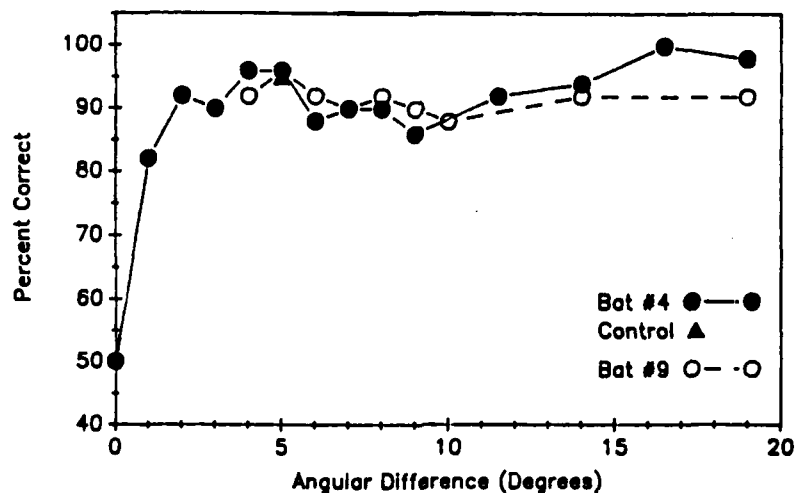
Figure 2. Transfer functions for two individuals before tracheal cannulation, after tracheal cannulation and after cementing to inhibit inflation of tracheal sac. All functions normalized relative to maximum value. Symbols as Fig. 1.

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1) *N. leporinus* reduces the intensity of emitted pulses so that intensity at the target is maintained constant from a distance of 1.5 m until the target is caught.

2) At a point in the pulse train when precise information about target position and characteristics may be required, *N. leporinus* selectively eliminates the fundamental of the FM component of the pulse. This has implications concerning the receiver type used by the animal.

3) Contrary to the generally accepted view, a high degree of overlap occurs between the FM component of the emitted pulse and the FM component of the echo from the target when *N. leporinus* is within 0.4 m of the prey.

4.2.2 *Strategy for the sonar tracking of moving targets.*
Suthers, Campbell, K.A.

The behavior of two bats was monitored as they dipped at a target moving perpendicular to their flight path which disappeared beneath the surface before the bats reached it. Both bats allowed for continued movement of the submerged target, and dipped at the position of the target rather than at the point of disappearance.

The head aim of the bats was monitored from above and found to be directed at the position of the target rather than at the point of interception. The flight paths of the bats, however, followed a more predictive course in most trials, as the bats flew towards the point of target interception rather than following a non-predictive path in which the bat simply flew towards the last detected position of the target.

Two bats were trained to discriminate between the horizontal angular separation of two pairs of rods, and were found to be able to distinguish between two angles different by only 1° (Fig. 2, see preceding page). Two other bats were trained to make an in-flight discrimination between targets moving at different transverse velocities, and were found to be able to distinguish between target velocities differing by 0.43 m/s.

4.3 Physiology and Lateralization in the control of birdsong.

4.3.1 *Lateralization of syringeal function during song by canaries.*
Suthers, Hartley, B.S.

The canary vocal organ, the syrinx, has two separate sound sources, one in the cranial end of each bronchus. Investigations of whether song syllables are produced unilaterally or bilaterally have provided two contradictory results, as one author suggested that almost all syllables are sung by the left side of the syrinx alone and only a few are produced by the right side alone, while another author suggested that both sides contribute similarly to all syllables. Our experiments, which involved unilateral bronchus plugging followed later by ipsilateral denervation of the syringeal muscles, attempted to resolve this disagreement.

The males with right bronchus plugs, singing on the left side of the syrinx alone, produced nearly normal songs, whereas the birds with left bronchus plugs, singing on the right side, sang quite poorly. Interpretation of these data is difficult because it is not clear

how syringeal function would be affected if the airflow rate through the intact side is increased above normal, nor is it known if the bird can compensate for bronchus occlusion. Nonetheless, we suggest that in male canaries most syllables are normally sung by the left side alone, with some syllables being produced by the right side alone and some being sung by both sides together.

Right nerve section did not affect the right bronchus plugged males' ability to sing, but the repertoires of the left plugged males were altered after left nerve section. We suggest two possible reasons why the right side might benefit from a normally configured (innervated) although silent (plugged) left side: either the right side is influenced by an anatomical link to the left side or perhaps the right syringeal muscles receive some neural input from the left nerve.

4.3.2 *Differential airflow through the right and left sides of the avian syrinx during song.*
Suthers, Hartley, B.S.

We have used a pair of heated microbead thermistors to simultaneously measure the airflow through the left and right sides of the syrinx of mimic thrushes, Brown Thrasher (*Toxostoma rufum*) and Catbird (*Dumetella carolinensis*), singing with an intact syrinx and vocal tract. During the great majority of song syllables air flows through both sides of the syrinx. Sometimes the pattern of airflow on each side is similar, but often it is very different. During a given syllable, for example, expiratory airflow may decrease on one side while increasing or remaining constant on the other. Occasionally a note is produced while air is flowing through only one side of the syrinx. Since both sides of the syrinx are exposed to the same positive subsyringeal (thoracic) pressure, these changes in flow must be due to variation in syringeal resistance caused by adduction or abduction of the syringeal membranes. The observed flow patterns indicate that some requires a very precise and complex motor control of syringeal muscles in which the two sides of the syrinx often act differently. Many syllables appear to contain separate contributions from both sides of the syrinx and the final vocal output depends on appropriate coordination of muscles comprising the right and left halves of the syrinx.

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5. Cognition and Decision Making

5.1 *The Role of Memory Operations in Memory and Storage*
Shiffrin, Murnane, and Smerek

Quite a bit of research supports the notion of 'transfer appropriate processing', and suggests that the operations involved in processing presented stimuli are an important component of the stored information. For example, Kolers showed that the reading of inverted text was facilitated by the prior reading of that text inverted a year earlier. The matching of the orientation was crucial for the effect. Fischer and Craik, and Morris, Bransford and Franks used different orienting tasks at study and showed better memory performance when tests matched the study task. Our research attempted to isolate experimentally the operations from the nominal contents of presentations, and to assess separately the costs and benefits of reinstating the study operations at test, and of inducing a different operation at test.

Subjects studied five word groups and either alphabetized the words or arranged them in the order of five provided categories. They were tested immediately to assess the accuracy of their operation. Much later the subjects were either tested for recognition of a five word group arranged in original order, alphabetical order, or category order, or were asked first to carry out another operation on a five word group and then tested for recognition. The operation either did or did not match that originally used. Among other characteristics, this design includes a condition in which the words and their order were identical at study and test, but a different operation was used.

The main results may be summarized easily. Recognition performance (d') was determined strongly by the match of operations at study and test, regardless of other variations. Furthermore, the recognition only control conditions showed both costs and benefits: reinstating the storage operation at test improved performance, but changing the operation reduced performance, relative to the control.

This work is the start of a series of studies aimed at examining the role and function of memory operations, and at distinguishing operations from nominal content in memory and retrieval.

5.2 *The List Strength Effect in Recognition Memory*

A number of studies have been carried out examining the effect of strengthening some items on a list upon recognition of other list items whose strength is not varied. A positive effect is said to occur when strengthening harms memory for other items.

5.2.1 *The List Strength Effect: I. Data and Discussion*
Ratcliff, Clark, and Shiffrin

We showed in seven studies that a positive list strength effect occurred strongly in free recall, weakly in cued recall, but was missing in recognition. In fact 14 of 18 conditions were negative in direction, 5 significantly so. Various artifactual explanations were ruled out. We also showed list-length effects in recognition in situations where list-strength effects did not occur.

5.2.2 *The List Strength Effect: II. Theoretical Mechanisms*
Shiffrin, Ratcliff, and Clark

We showed the recognition results from Part I to be inconsistent with all current memory models, including composite distributed models and neural net models. An attempt was made to modify these

models to accommodate the results. The SAM model of Gillund and Shiffrin (1984) could be made to handle the results using the following assumption: 1) Items are stored separately, not in composite fashion; 2)repetitions of an item are accumulated into one memory trace; 3) recognition operates by accumulating activations of the different memory traces for items from a given list; 4) activation of a trace by an unrelated test stimulus gets lower, the stronger is the trace (this is called a 'differentiation' hypothesis); 5) recall operates as a search process involving successive stochastic sampling of memory traces in proportion to the storage strength.

Successful variants of other extant models could not be found, and the analyses of these models suggested important constraints that the list strength data imposes on future model development.

5.2.3 *The Production of Positive List Strength Effects*
Shiffrin and Murnane

The model described above assumes repeated items are accumulated into one memory trace. If so, then a procedure inducing subjects to store repeated items separately should produce a positive list strength effect in recognition. We presented five word sentences sometimes containing repeated words, but no two sentences shared more than one word. The different sentence contexts should have induced separate store, and hence repeated words should have reduced single item recognition performance for nonrepeated words on a later test. Such a strong list strength effect was found, although repeating entire sentences eliminated the effect, replicating earlier results.

5.3 *A Test of the Composite Memory Hypothesis*
Shiffrin and Marinelli

The list strength findings discussed above suggested separate storage of traces of items. Many current models assume composite storage in which the same vectors, matrices, or networks of weights are used to encode many items simultaneously. To test this point directly, we presented exemplars near a category prototype, but not the prototype itself, and then tested for recognition and recall. Even models that posit separate storage assume composition across traces to occur during recognition, so all models predict high levels of false recognition of the nonstudied prototype. However, models like SAM (Gillund and Shiffrin, 1984) assume recall to operate by separate access to separate traces, so recall of nonstudied prototypes should be low (not zero, due to guessing, reconstruction, etc.). Composite storage models predict high levels of recall of nonstudied prototypes, in contrast. In four studies, we used orthographic and phonological prototypes, with both word and pseudoword stimuli, and also semantic prototypes for words. We compared recall and recognition advantages for pairs of items (exemplars and nonstudied prototypes, or exemplars and exemplars). Even when false recognition of a prototype was higher than some exemplar, recall was much lower; in general the recall–recognition function for exemplars versus nonstudied prototypes was quite different than the function for exemplars versus exemplars. The results suggest that composition of traces occurs at retrieval rather than storage. Work is now proceeding on developing neural net models incorporating this characteristic, along the lines of Steven Grossberg's neural net models.

Note: From August 1 1988 – February 1, 1989, Dr. Shiffrin was on sabbatical at the University of Queensland, Brisbane, Australia. During this period he made the following presentations:

1) "On composite memory models." *Math Psychology Meetings*, August 1988 – Chicago.

2) "List Strength Effects and Memory Models." *International Congress of Psychology*, September 1988 – Sydney, Australia.

3) "On Models of Recognition and Recall." *Memory Conference* – University of Queensland, Brisbane, Australia.

4) "On Memory Models and Composition." *Australian Mathematical Psychology Meetings*, September 1988 – Armidale, Australia.

5.4 *Machine Aided Detection and Recognition.*

In this research Robinson and his colleagues have considered a person–machine system consisting of an automated alarm and a human monitor. The task of the human is to monitor a noisy channel on which information about a potentially dangerous condition may appear. The alarm system monitors an independently noisy channel for information about the same threatening condition. Using basic concepts of statistical decision theory, the Contingent Criterion (CC) Model of multi–stage decision making has been developed. According to the model, the human should establish two criteria for responding: one contingent on an alarm from the automated detector, and one on no–alarm. The model predicts large gains in performance compared to either detector alone. Our initial work on multi–stage decision making began with a series of laboratory experiments in which human listeners were aided by an automated detection system. This work, some of which has been reported previously (Sorkin and Robinson, 1984; Robinson and Sorkin, 1985) shows that performance of the system is reasonably well described by the CC Model, although performance of the human is less than optimal. Over the last several years, we have continued to develop the CC Model, to investigate the effects of additional variables on the performance of the model, and to expand the model to include target identification. In particular, progress has been made in each of the following areas of investigation.

5.5 *Effects of inter–channel correlation*
Robinson

In our initial development of the CC Model, we assumed that the noise in the alarm–system channel is uncorrelated with that in the channel monitored by the human operator. Such an assumption is probably unrealistic in many "real–world" situations. We have since investigated the degradation in performance which occurs with increased correlation between the two channels. The predictions of the model indicate that, although there may be a considerable performance decrement when the correlation is near unity, the model is quite robust, and system performance can exceed that of either detector alone even with correlations as high as 0.50.

5.6 *Effects of signal probability and values and costs*
Robinson, Rickert

Other parameters of importance in determining the performance of combined detection systems are the *a priori* probability of the signal and the values and costs of the possible outcomes of a decision. In our past work, we have evaluated system performance using measures derived from the Receiver Operating Characteristic (ROC), such as P(C) and d'. These measures are not affected by changes in *a priori* probability or values and costs. As a result, we have now turned to measures based on Expected Value. Analyses based on Expected Value suggest that the advantage of a multistage decision making system over a single–stage one is highly dependent on *a priori* probability and on values and costs. In fact, under some circumstances, a single–stage system is preferable. This research is continuing, with additional support from the Naval Weapons Center, China Lake, CA.

5.7 Target Identification
Robinson, Rickert

More recently we have attempted to expand the CC Model to include signal classification (identification) as well as signal detection. This effort draws on the work of Nolte (1967), Nolte and Jaarsma (1967), Green and Birdsall (1978), and Starr, Metz, Lusted, and Goodenough (1975). Our efforts to date suggest that the performance of a system consisting of a human operator and an automatic signal classifier can be significantly improved compared to either subsystem operating alone. This research is continuing, also with additional support from the Naval Weapons Center, China Lake, CA.

There are two important observations that may be drawn from our work in multi-stage decision making. First, although the laboratory experiments indicate that combined system performance (human-plus-automated detectors) was less than optimum, no effort was made to train subjects in the proper placement of their criteria. It is likely that human operators can be trained to use the available information more efficiently, and to set criteria which will lead to more nearly optimum system performance. A second observation is that system performance is dependent not only upon the behavior (sensitivity and criterion placement) of the human operator and the criterion (threshold or alarm set-point) of the automated alarm system, but also upon *a priori* signal probability and the values and costs. System performance may be improved by changing any of these parameters of the system.

5.8 Information Integration
Robinson, Rickert

Our work in this area began with two major goals. The first was to understand the processes by which humans integrate information over time or over channels. The "multiple look" problem is the basis for our initial work in this area. The basic question is, "How much additional information is gained by allowing observers more than one observation in a detection or discrimination task?" The second goal was to develop and evaluate models of "internal noise." The amount and rate of improvement in performance with an increasing number of observations will depend not only upon the amount of internal noise, but upon the level of processing at which the internal noise is added.

Previous research (Swets, Shipley, McKey, and Green, 1961; Swets and Birdsall, 1978; Swets, Green, Getty, and Swets,1978) has demonstrated that performance in signal-in-noise detection tasks improves as listeners are allowed more observations. According to signal detection theory, d' should increase as the square-root of the number of observations. This result assumes that the decision statistic is any monotonic transformation of the mean of the n likelihood ratios obtained from the n observations. In some versions of the derivation, internal noise is added prior to the formation of the decision statistic in order to account for the less than optimal performance at $n=1$. This does not alter the square-root-of-n prediction. Previous research, usually involving the detection of repeated signals in a noise background, has supported the square-root-of-n prediction. However, the earlier work provided only limited tests, since the use of signals in a noise background precluded exact specification of the noise and signal-plus-noise distributions on an observer's decision axis. Further, only small values of n were used. Our research has extended this work by developing a unique para-digm that allows exact specification of the distributions on an observer's decision axis (Berg and Robinson, 1987). In this paradigm, the observer's task is to judge from which of two distributions on frequency a sequence of n tones was sampled. Results from several experiments indicate that listeners can approach the theoretical d' for $n=1$, but do not follow the square-root-of-n rule, even for small n.

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In order to account for the failure of the square–root–of–n prediction, we have assumed an additional source of internal noise (Robinson and Berg, 1986; Berg and Robinson, 1987; Berg, 1987). This type of internal noise may be thought of as additional variance introduced by uncertainty of the decision criterion, changes in response bias, or memorial factors associated with the decision statistic. Briefly, then, in the "partitioned variance" model, as we have termed it, internal noise is added at two stages: (1) at the periphery, before a decision statistic is formed and (2) centrally, after the statistic is formed. As we have previously reported, the model does an excellent job of describing the data of the sequential tone experiments, as well as those of a similar experiment in which the tones are presented simultaneously (Grantham, 1987). We have also developed techniques for estimating the amount of internal noise added at each of the two stages and techniques for determining the degree to which each tone in the sequence contributes to the observers' final decision (Sorkin, Robinson, and Berg, 1987). Our results indicate that subjects are highly idiosyncratic in the degree to which various portions of a temporal sequence contribute to their decision: some subjects appear to show a primacy–recency effect while others show roughly equal weighting of the tones in a sequence.

5.9 Response latency and decision criterion in psychophysical decisions.
Espinoza–Varas, Watson, Patterson, Kyle

A manuscript has been prepared for submission to *Perception and Psychophysics* describing earlier data on the effects of decision criterion on response latencies in psychophysical decisions. The response latency to a given stimulus was found to vary inversely with the distance between the stimulus and the current response criterion, and with the probability of the response. These effects were observed for both visually presented two–digit numbers and pure tones under three different decision tasks. (Original & experimental work supported by an NIH grant to the Central Institute for the Deaf, data analyses and manuscript preparation supported by NIH and AFOSR grants to Indiana University).

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Ratcliff, R., Clark, S., and Shiffrin, R.M., The list–strength effect: I. Data and Discussion. Revision submitted to *Journal of Experimental Psychology: Learning, Memory and Cognition,* June 1989.

Ratcliff, R., Clark, S., and Shiffrin, R.M., The list-strength effect: II. Theoretical Mechanisms. Revision submitted to *Journal of Experimental Psychology: Learning, Memory and Cognition*, June 1989.

Manuscripts in Preparation

Berg, B.G., Robinson, D.E. and Grantham, D.W. Multiple-observation tasks: A partitioned-variance model.

6. Connectionist Models of Sensory and Cognitive Processes

6.1 *Recognition of Melody Fragments in Continuously Performed Music.*
Port, Anderson, Gasser, Lee

An important step in perceptual modeling is the development of models that function continuously and recognize patterns distributed in time. Apparently connectionist models can do this in a biologically plausible way by processing only a single frame of input at a time. Such a system must construct a representation of past inputs and exhibit memory that allows recognition of patterns that extend over a number of input frames. If a system is to deal with temporally distributed patterns have varying durations, then use of a built-in restart signal to begin analysis from a standard initial network state, (eg, at the beginning of each perceptual trial) is ruled out. External reset, as found in unfolded networks (Elman, 1986b), fixed window networks (Elman, 1988) or fixed-length dynamic windows(Anderson, 1988) greatly reduces the biological plausibility of a system. Some means for resetting the system that can be partly controlled from the bottom up is required (cf. Grossberg,1980, Grossberg, 1987).

We have demonstrated (Port & Anderson, 1989, in press) that a modification of real-time backpropagation (Williams & Zipser, 1988) can be used to train a network to recognize continuously presented melodies played by hand on a keyboard. Our network, shown in Figure 1, has recurrent loops of connections to store information about the history of the signal. All edges have learnable connections. The short-term memory employed, consisting of 'state nodes' that take input from previous predictions as well as label outputs, contrasts with memory that is a literal record of previous inputs (as in delay-line systems such as Waibel, 1988) and is similar to the structure of several other systems (Jordan, 1986, Elman, 1988, Anderson, Merrill & Port, 1988). To permit reset of the network when a partially recognized pattern must be rejected, we use sigma-pi nodes. These allow the activation of nodes in the input clique and the state-node clique to gate each other. We found that recognition of sequential patterns was greatly improved when the system was also trained to predict the next input. Disconfirmation leads to rapid reset to the waiting state by the sigma-pi nodes.
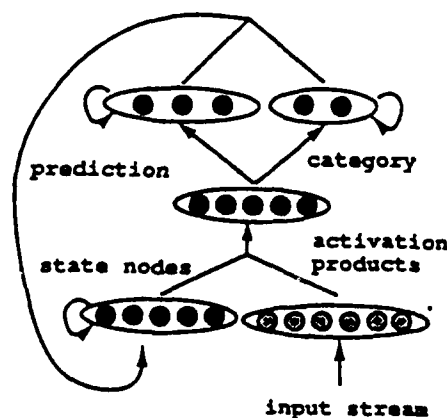
The architecture of the network employed.

In the experiment, the targets were two very similar one measure fragments of tunes produced by hand on an electronic keyboard. Several repetitions of each melody were recorded and digitized. Fast-Fourier transforms were made of each measure and maximum obtained within 6 bins, one for each note employed. Numbers derived from these amplitudes were used as inputs to the network. The network was fed randomly ordered measures in a stream and trained to both predict the next note and to recognize occurrences of the two target measures.

The system could distinguish the two target measures from all others with d's of 2.03 and 2.75. Two very similar measures were distinguished from each other when presented in context with d's of 1.64. The results showed that a sparse recurrent network can learn to recognize several target patterns from other sequences and differentiate them from each other even when the primary difference between them lies in temporal properties and despite natural variability in production. This system 'listened' continuously, without an a priori input window other than the minimum time frame for the spectral analysis. This experiment is a step toward a continuously functioning dynamically controlled general detection system for auditory targets.

6.2 *Perception of Nonspeech Stimuli Patterned on the Temporal Structure of English Words.*
Port, Mills, Anderson, Gasser

Words having the same sequence of acoustic segment types typically differ in temporal detail due to differences in stress on segmental components. We have recently shown that these differences in temporal detail can be used to identify words using linear discriminant functions (Port, Reilly & Maki, 1988; Port, Reilly and O'Dell, 1986; Port and Crawford, in press). In a pilot experiment we sought to determine how well human listeners could use this information to identify words, using as subjects both native and non-native speakers of English.

The five words and phrases *basket, boozed up, bust it, buzzed it'* and *dues paid* were recorded by one speaker and the durations of major segments measured (the first vowel, the fricative, the medial stop closure, stop aspiration, final vowel and final stop closure duration). Then 5 synthetic tokens were constructed from the measurements using a digital editor. Each speech segment was replaced with a similar non-speech sound: a tone for the vowels, noise for the fricatives and silence for the stop closures. Both American and Korean listeners were asked to identify each stimulus with one of the original English phrases.

The task was difficult, as expected. Before training, both groups performed at approximately 35% correct. The Koreans' performance improved more than the Americans' after training (75% vs. 50% correct). This seemed initially surprising until we computed a Euclidean distance between the 5 stimuli. After training, Korean, but not American, errors could be predicted well by the Euclidean distance between the temporal patterns. That is, the Koreans learned the distinctive temporal properties of these particular tokens to identify them. The Americans, on the other hand, may have suffered interference from their knowledge of natural variation in the timing of these words which prevented them from exploiting the idiosyncrasies of the five tokens. The Koreans, as non-native speakers, were more free to focus on token idiosyncrasies, and to treat the task as one of simple auditory learning.

This preliminary work suggests the feasibility of future studies using a much larger set of nonspeech stimuli based on the temporal patterns of many naturally-produced tokens of each word

type. In such a context, native proficiency in a language should be an advantage for categorization and different linguistic backgrounds should lead to clear differences in performance. Such stimuli have many obvious similarities to the tone-sequence stimuli used by other Institute investigators (eg, Watson & Foyle). But since these stimuli are closer to real speech, they can be used to estimate the effects of long-term linguistic experience.

6.3 *Investigating Second Language Transfer with Auto-Associative Networks*
Gasser

A major focus of research on second language acquisition concerns the nature of the effects of the first language (L1) on the second (L2) and vice versa. While it is generally agreed that transfer has a role to play in L2 acquisition, the details of how it operates appear to be very complex (Gass & Selinker, 1983). The connectionist framework provides an excellent means of testing various notions about transfer in second language acquisition because transfer is precisely what connectionist models are good at. Once a network has learned an association of a pattern P1 with a pattern P2, when it is presented with a new pattern P3, this will tend to activate a pattern that is similar to P2 just to the extent that P3 is similar to P1.

The network for the simulations is an auto-associator in which input patterns are mapped to identical output patterns via a layer of hidden units. Each input pattern is intended to represent a simple clause consisting of two words, a subject and a verb. The input and output layers consist of three groups, a pair of "language" units, representing the language being learned or processed; a set of form units, representing the words and their positions in the clause; and a set of content units, representing the word meanings and their roles in the proposition denoted by the clause. The roles for this example are simply AGENT and PROCESS. Figure 1 shows the basic structure of the network. Each of the ovals in the figure contains a number of units. Heavy arrows signify complete connectivity between groups of units. That is, every input unit is connected to every hidden unit and every hidden unit to every output unit.

Figure 1: Architecture of Network Used in Simulations
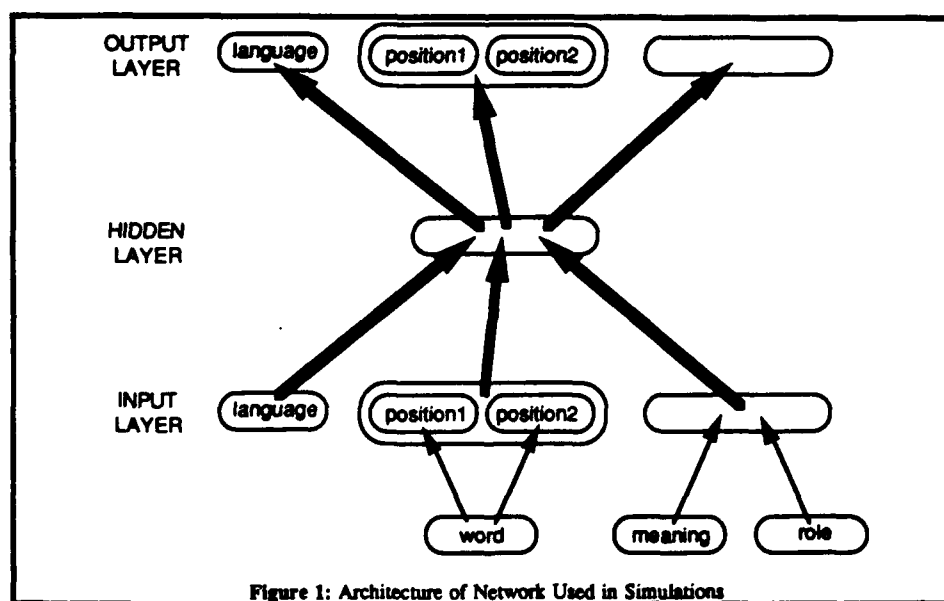
To create the input patterns, an arbitrary bit string of length 7 is assigned to each word and word meaning. Within the set of 14 form units, 7 represent first position and 7 second position in the clause. For the pattern representing the clause *John sings*, the units corresponding to the pattern for John are turned on or off in the 7 first-position units, and those corresponding to the pattern for sings are turned on or off in the 7 second-position units. For the content units, roles are assigned binary strings of length 5, and each of the 35 content units represents the conjunction of a meaning element and a role element. The pattern across the 35 content units represents both the meaning of the current AGENT and the meaning of the current PROCESS. Thus a complete input pattern for the clause *John sings* consists of a pattern representing L1 on the language units, a pattern representing the word *John* on the first- position form units, a pattern representing the words sings on the second-position form units, and a pattern representing JOHN as AGENT and SING as PROCESS on the content units.

The system was trained using back-propagation (Rumelhart, Hinton, & Williams, 1986) to associate input patterns of this type with identical output patterns. For the simulations described here, 25 hidden units separated the 51 input and 51 output units. There was complete connectivity between the layers; thus there were 2550 adjustable connections in all. A small set of words and meanings was used for the training patterns: 6 verbs and verb meanings and 6 noun and noun meanings. The training set consisted of randomly selected pairings of noun-verb, AGENT-PROCESS, except that a small set of combinations was never trained on. After training on 1100 such patterns (many repeated of course) the network had learned to map input patterns to themselves with a very small error rate. Following training the network was able to successfully complete partial input patterns. Input patterns in which the words were missing (with form units all set to a default activation of 0.25), corresponding to a parsing task, resulted in output patterns with the appropriate activation on the form units. Input patterns in which the content was missing, corresponding to a production task, resulted in output patterns with appropriate activation on the content units. Results were only slightly worse for patterns which the network was not trained on. For example, though the network never saw the pattern for the sentence John drinks, it was able to correctly turn on the output units for the words *John* and *drinks* in the first and second position groups respectively when presented with an input pattern giving only the meanings JOHN and DRINK together with their roles.

To test transfer to a second language, a second set of input words was then generated. In the first 2 simulations, these bore no relation to the corresponding first language words. In the third and fourth simulations, each differed from the corresponding L1 word by only one bit. After the network had been trained on the L1 patterns as described above, it was trained on both L1 and L2 patterns for a total of 2200 more repetitions. In addition to the difference in lexical items, the L2 in some of the simulations differed in constituent order; that is, for these simulations the L2 had verb first and subject second. Of interest was the speed with which the system was able to learn the L2 patterns.

The important effects observed were the following:

1. The L1 patterns suffer interference from the L2 patterns. Even after 1100 additional training iterations, they do not recover their previous accuracy in any of the simulations.

2. The L2 patterns remain less well-known than the L1 patterns throughout.

3. Though the L2 patterns are initially difficult for the network, they are not as difficult as the L1 patterns were when they were first presented to the network.

4. It is more difficult for the network to learn the L2 patterns when the word order differs from the L1 patterns than when it is the same. This difficulty is reflected not only in the speed with which

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the L2 patterns are learned but also in the degree to which the L1 patterns are interfered with. The word order difference also seems to have less and less of an effect on mastery of the L2 (and interference with the L1) as learning continues.

5. There is some evidence of an advantage when the L2 words are similar to the corresponding L1 words, but again this difference seems to disappear as more patterns are presented.

6. The effect of different word order appears to be greater with similar words than it is with unrelated words.

6.4 *Extracting Tempo from Rhythmic Input*
Gasser, Port, Anderson

People have the ability to detect, learn, and generate rhythmic patterns. This is reflected in linguistic and locomotive, as well as musical, behavior. Rhythmic patterns must be stored in a form that is to some extent independent of the tempo at which they are encountered because people can recognize learned patterns presented at novel tempos. Thus it is reasonable to assume that rhythmic input is analyzed into a tempo component and a tempo-independent component.

This research is concerned with the development of a connectionist system which models aspects of tempo extraction, maintenance, and production. The network takes simulated input in the form of activation on an input unit and generates matching periodic output which continues until it is interfered with by another pattern or random noise. In addition to the input unit, the network has three main components, a set of beat detection units, which are sensitive to changes in input intensity; a set of tempo units, which respond to different beat frequencies; and a set of pattern units, which recognize and store the tempo-independent aspects of rhythmic patterns. The pattern component is currently under development and is not discussed further in this report.

The system is an adaptation of a Hopfield network (Hopfield, 1984) with deterministic, continuous-valued units. The model differs from the Hopfield paradigm in that not all connections are symmetric, as described below. The heart of the system is the tempo component, which has already been successfully tested in simulations. It consists of a bank of unit pairs, each with a characteristic oscillating frequency. Joining each pair there are asymmetric connections, positive in one direction and negative in the other. In addition, each unit has a self-excitatory connection. The output of each pair (and the input to the pattern units) is essentially the difference between the outputs of the two component units.

When a pair of tempo units receives sufficient input from the beat detection units, it begins to oscillate with a frequency which depends on the weights on the self-excitatory connections and the asymmetric connections between the units. These weights are pre-set in such a way that the pairs have oscillating frequencies varying from 10 to 50 time steps.

For the simple system just described, the tempo pairs will continue to oscillate indefinitely once they have been started up, leaving the system incapable of distinguishing one tempo from another. What is needed is a way for tempo pairs which are not in phase with input beats to be turned off. This is achieved by adding a degree of instability to the tempo pairs through the use of modulated connections (Dehaene, Changeux, & Nadal, 1987). The weights on the asymmetric connections joining the units in a pair vary with the output of the source unit for each connection.

In this form the tempo pairs have two fixed-point attractors in addition to their periodic attractor. When an oscillating pair is exposed to high positive or negative input from the beat detection units at a point which is not near the point of maximum or minimum output of the pair, the pair tends to fall into one of the fixed-point attractors. In this fashion only those pairs with frequencies close to the tempo of the input pattern continue to oscillate after several beats have been detected. If the input beats stop temporarily, the tempo pairs which are oscillating continue to do so. Similarly, pairs with frequencies which are integer multiples of the input tempo continue to beat.

Tempo pairs which are close to one of the fixed-point attractor states do not oscillate in response to input. To allow the system to detect new rhythms, there is a noise term in the equation determining the weights on the asymmetric connections. The amount of noise increases as a function of the degree to which the sum of the outputs of the tempo pairs oscillates. When no pairs are oscillating, the noise term increases. This has the effect of destabilizing the non-oscillating pairs so that they can begin to oscillate in response to input.

Articles and Published Abstracts

Gasser, M. (1989). Connectionism and universals of second language acquisition. *Studies in Second Language Acquisition*, **12**, (in press).

Gasser, M. (1989). Robust lexical selection in parsing and generation. *Proceedings of the Eleventh Annual Meeting of the Cognitive Science Society.*

Port, Robert and Crawford, Penny (1989). Incomplete neutrailzation and pragmatics in German. *Journal of Phonetics*, **17** (in press).

Submitted Manuscripts

Gasser, M. (submitted). A connectionist approach to the perception and production of rhythmic patterns. *Third International Workshop on AI and Music.*

Gasser, M. (submitted). Extracting tempo from rhythmic input. *Third Conference on Neural Information Processing Systems.*

Merrill, J. W. L. & R. Port (submitted) Fractally configured neural networks. *Neural Networks.*

7. Institute Facilities

7.1 Multi-modality Laboratory (DEC-based system)

The following equipment has recently been installed in the Institute's new Multi-modality Laboratory.

1. Central Computer System. The CPU used in this system is the Digital Equipment Corporation, Micro-PDP 11/83 (KDJ11-BF). This is a 16 bit microprocessor implementing full PDP-11 compatibility and running at a CPU clock speed of 18 Mhz. Main memory, 4 Mbytes of RAM, connected by the high speed PMI bus, is supplied by the Clearpoint QED-1/4MB. The date and time are maintained in a battery-powered calendar-clock (Digital Pathways, a TCU-50DYR) that allows the system software to load into the operating system, as part of its initialization procedure, the correct time and date. This is a valuable function because the time and date are used to identify both program and data files. The logic modules comprising this Micro-PDP 11/83 computer system are housed in two MDB chassie boxes which provide for the 22 bit Qbus backplane interconnection system. The first box (a MDB MLSI-BA11-2200F), which houses the CPU, is an eight quad-slot module backplane, with three slots being wired for PMI memory. The second box (a MDB MLSI-BA11-3000F) is an eight quad-slot expansion backplane. These two chassie boxes are housed in a pair of 60" equipment racks which allow sufficient room for all system peripherals as well as the real-time laboratory instrumentation.

2. Peripheral Devices. The system's peripheral resources are divided into three general groups: disk, magnetic tape and serial devices. The main secondary storage is a large (368 Mbyte) high performance CDC Winchester disk system. Also for compatibility to the large number of existing laboratories at Indiana University and our many other research colleagues using Digital Equipment Corporation PDP-11s, a used 8" dual floppy disk system, an RX02 was included. Industry standard 1/2" magnetic tape capability is provided on the system by using an Emulex TC01 controller which is coupled to a Kennedy 9100, 800/1600 bpi, 75 ips, magnetic tape transport.

A variety of serial devices are connected to the system using several different interface modules. The main system console is a Digital Equipment Corporation alpha-numeric CRT terminal, a VT320-BA; which is connected to the one serial line that is integral to the KDJ11-BF CPU module. Four general purpose serial lines are implemented via a Digital Equipment Corporation DLV11-J module. These lines support the system printer, a Digital Equipment Corporation 200 cps dot matrix printer, an LA75; and a used Digital Equipment Corporation VT100 terminal used for subject I/O. The remaining two lines of this module are unassigned and are reserved for future expansion. A higher performance buffered four line serial multiplexor, a Digital Equipment Corporation DZV-11, is used to connect a variety of existing terminals in the investigators' laboratories (i.e. VT100, VT220, and VT240), to support time sharing activity when the system in not in the exclusive real time experimental control / data acquisition mode. One additional serial line is attached to the system by a Digital Equipment Corporation DRV11-E serial line which provides full modem control. This device is attached to a Practical Peripheral 2400 baud modem (PPM-2400) to allow connection with the campus computing system and networks and computing resources beyond the local computing environment.

3. Real-Time Laboratory I/O and Stimulus Control. A variety, both in type and capability, of real-time devices have been procured and installed on the system to maximize our ability to implement our original instrumentation needs as well as to respond quickly to new instrumentation requests as they arise.

Several general purpose devices have been installed which can meet a variety of real-time instrumentation needs. An alpha-numeric video interface, which provides a display of 24 lines by 80 col-

umns, using standard RS-170 video output, is implemented by a Peritek Corporation VRQ-A. This signal is presented both at the console terminal work station as well as at the subject station on 9" video monitors. This display is used primarily for providing instruction and feedback to the subject during on-line experiments. It may also be used as a video scratch pad display by the operator during off-line operation. Three modules by Andromeda Systems provide medium capability A/D, D/A functions as well as programmable timing. Analog to digital (A/D) conversions are provided by the ADC-11. This module is a functional superset of the Digital Equipment Corporation ADV11-C, and provides 16 single ended or 8 differential input analog channels with 12 bit resolution for lower speed data acquisition needs. One A/D application already in place is an X/Y joystick that can be used to control the positioning of the cursor or display primative when using one of the visual presentation devices. This joystick may also be used for any response input in which a judgement over a continuous range is required. Digital to analog (D/A) conversions are provided by the DAC-11 module which is a functional superset of the Digital Equipment Corporation AAV11-C. This module provides four 12-bit D/A outputs for lower speed control applications. The third Andromeda Systems module is a programmable clock, a PRTC-11, (this module too is a functional superset to its Digital Equipment Corporation counterpart, the KWV11-C) which is used to time program intervals as well as subject response latencies. Each of these three Andromeda Systems interfaces are connected to a connection I/O panel which makes all I/O signals easily available to the user via BNC or banana jack connectors. Subject responses and cueing are handled by a single-subject version of the Response Box Controller system used in many of the investigators' individual laboratories. This system provides a buffered 8-bit data path on both input and output. This system provides electrical signals to facilitate a wide variety of response manipulanda and indicators; push buttons, keyboards, keybads, switch plates, LEDs, incandescent lamps, relays, sonalerts and many other devices are easily connected to existing signals and only the necessary cabling is required for proper operation.

The instrumentation used for the presentation of auditory stimuli is the most complex stimulus presentation sub-system. The audio system originates with two high speed 12 bit D/As implemented with a Data Translation DT2751 module. Acoustic signals are generated using the PCM technique and a Data Translation programmable clock, a DT2769, is used for the purpose of synchronizing the A/D outputs from the DT2751. Because the PCM control pulses originate from a programmable source this system is not limited by a fixed sample rate; but rather only by the throughput of the system at the high end and the setting of the fixed and variable low pass filters used to condition the audio signal. A Digital Equipment Corporation 16 bit parallel digital interface (DRV-11) provides 16 data lines that are input to a custom 16 bit 4 port digital multiplexor. This multiplexor is used to control several audio devices. The first two channels of this digital output multiplexor are used to control two programmable attenuators. Each side of the two channel audio signal is run through one of these attenuators each of which is capable of attenuating the audio signal from 0 through 127 dB, in 1/4, 1/2 or 1 dB steps. The third port on the digital output multiplexor is used to conrol a programmable function generator (a Krohn-Hite 5500AR) which serves as another source of audio signal. Two other off line audio sources, a white noise generator, and an unassigned auxiliary (AUX) input signal are all fed into a two-channel signal conditioner. The signal conditioner, for each of the two audio channels independently; (1) selects or mixes from the four audio inputs (D/A, function generator, noise, or AUX source); (2) performs low-pass filtering from either a 4.8-Khz or 10-Khz fixed filter, for the two D/A signals, or a manually programmable low-pass filter, a Krohn-Hite 3202R, for any signal path; (3) provides for level control calibration adjustment with a bank of manual attenuators in 1-dB steps, over an attenuation range of 0 to 99.9 dB; (4) provides amplification to drive a pair of quality Boston Acoustic speakers (A60) using a Crown D-75 power amplifier and a series of matched and calibrated 300-ohm Telephonics TDH 39 earphones.

Experiments which require the use of tactile stimulation have available two devices. Two custom tactile controllers, each capable of providing buffered output for up to 144 individual tactile stimulator pins, have been constructed using a digital I/O foundation module which supports DMA transfers, an MDB Systems MLSI-11B. These two controllers are identical, and are capable of being used one at a time or simultaneously. Further, each is able to control one of two tactile stimulators giving us the means to use two different tactile stimulators together or two of the same type at the same time. The two tactile stimulators available are the commercially available Optacon, a reading machine for the blind, from Telesensory Systems, which provides a tactile array of 6 columns by 24 rows to the finger-tip, and a locally-designed and constructed tactile stimulator for one or both forearms, each having up to 30 individual stimulators arranged in rows of up to 5 stimulator elements.

Two independent systems are available for visual stimulus presentations. The first is a color video graphics display system. A video display interface from Peritek Corporation, a VCK-Q, provides a color raster scan display of 1024 by 1024 pixel resolution. Each pixel in this display may have a color selected from a color palette of 4096 colors. A high quality, 19" color monitor, a Mitsubishi HJ6905, is used to display this video image. The second visual display system is for Tachistoscopic speed pres-entations, ones which have very short presentation invervals and can be turned off very quickly. This system is implemented using an X-Y point-plot scope analog system. A high speed dual channel D/A converter, a Data Translation DT2751, with integral Z axis control, is used to plot a series of dots on the face of a fast phosphor X-Y oscilloscope (a Hewlett Packard 1340A with P31 phosphor). This system is capable of display times in the single digit millisecond range and can display up to and be-yond 500 points per screen.

4. Software Environment. The software installed on this system comes from a variety of commer-cial and research laboratory sources. The main operating system is RT-11 (currently Version 5.4G) from Digital Equipment Corporation. A second compatible and overlapping operating system, TSX Plus, from S & H Systems is used when real-time experiments are not being conducted and provides a multi-user operating environment allowing several users to work simultaneous on program develop-ment, stimulus preparation, data reduction/analysis or other computing tasks. Other commercial soft-ware on the system includes the Fortran IV and Fortran 77 programming languages also from Digital Equipment Corporation. Software subroutine libraries to support the Data Translation modules and the Peritek Corporation video display modules have been obtained from their respective manufacturers.

A library of software exists for all of the custom stimulus presentation and response collection devices that were developed in the individual laboratories of the investigators cooperating on this pro-ject. Care has been taken in the design and construction of this facility to capitalize on this existing software. We expect that as specific experimental needs arise our existing software will be refined and upgraded to support the individual stimulators and real-time devices, which have heretofore been used individually, into simultaneous operations providing us the true multi-modal stimulus presentation and control system originally envisioned.

7.2 Multi-modality Laboratory (Mac-based system)

A Macintosh IIx has been developed as a general-purpose laboratory platform for the develop-ment of multimodal psychophysical paradigms, stimulus generation, data acquisition and on-line analysis, and management of data. The Mac contains the standard 68030 CPU, 80 MB hard drive, 4 MB of linearly addressable RAM, and raster-based 8 bit color video coprocessor. In addition, a MacAdios analog/digital I/O coprocessor has been incorporated for audio sampling, acquisition of scanned images for dipole visual stimuli, and output of two-channel auditory stimuli. Two extra video coprocessors (standard variety) are installed to support the two additional monitors used in periph-eral vision experiments.

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The availability of reliable hardware/software modules and efficient software development environments were factors in our decision to use a Mac-based system for this application, rather than a PDP 11, with its 16 bit address space and the complexity of sharing data between concurrently loaded programs. An 80386 system was briefly considered, but was rejected; the existence of multiple competing standards makes it difficult to find a workable combination of memory, video hardware, I/O subsystems, system software and development environments.

The user-friendly interface of the Mac is especially appropriate for experiments using naive subjects, while the operating system lends itself to event-driven programming mixed with real-time I/O operations, which can be automatically synchronized across multiple video boards via system calls.

A typical experiment starts with the subject being led through a login process and initialization of relevant parameters. The video lookup tables are loaded with ramps corrected for non-linearity in the output devices, and a model of the visual stimulus is then computed or loaded from a file. Auditory output hardware is initialized, and the experiment begins. The subject is cued, on a trial-by-trial basis via the audio channels to attend to a specific visual task. If the current presentation contains a visual stimulus, the appropriate LUT is ramped to its desired intensity. This ramping is fully synchronized with the 66.67 Hz frame rate of the monitor, and is the only time-critical portion of the program. In the current Mac II, there is sufficient time to compute new LUTs for two 8-bit monitors during each frame. When the experiment concludes, or is interrupted by the subject, simple statistics are computed and saved, along with the raw data, in formats compatible with in-house statistical programs and commercial data manipulation packages.

7.3 Interlaboratory Computer Network

A great deal of the Institute's research is directed toward the development of models of information processing. The development and testing of models in the areas of decision making, cognitive processes, sensory processes, speech-motor control, and human-computer interaction require considerable computing power to search parameter spaces, identify the form of those spaces, and find best fits to data. In cases in which the models are not mathematically tractable, Monte Carlo methods or other computer simulations must be used to search parameter spaces and otherwise evaluate models. The group of investigators who share common interests in modeling in the areas mentioned above have benefited from improved computing resources used both for interactive modeling and for computer-based communication among the various laboratories. During the second year of the current award we purchased and installed additional computer workstations, with more extensive processing power than personal computers, and which greatly facilitate inter-laboratory communications. The Institute network, now connecting our eleven affiliated laboratories, adequately handles the data processing and communication needs of the investigators, postdoctoral fellows, graduate students, and visiting scientists. This network also has been connected to another network of *Apollo* workstations at Indiana University. The total network of more than 50 workstations now includes laboratories and offices in the Departments of Computer Science, Linguistics, Mathematics, Psychology, Cognitive Science, Speech and Hearing Sciences, the School of Optometry, and the central office of the Institute. We are able to share resources such as disk space, printers and plotters, external network connections and have also achieved considerable efficiency and economy in terms of maintenance and system programming. The *Apollo* network makes it extremely convenient to share computing power in single or multiple-node applications, as well as making common data bases of software available to all work stations.

Our Institute network now includes 17 *Apollo* workstations (10 purchased on URI/AFOSR funds) in various departments and buildings at Indiana University, running Apollo's version of the *BSD Unix*

operating system. In addition, we also have access to the research computers of the Bloomington Academic Computing Services: (BACS,) VAX 11/8800s, VAX 11/8600s, and VAX 11/780s. Our computing environment has been designed for use in modeling, gathering test data, doing various statistical tests, graphics displays in addition to serving as a link between the members of the institute. Through its connection with BACS, the *Apollo* network also serves as a major link between local computing resources and external computing facilities inside and outside the university. Last, the network computers serve as general-purpose wordprocessing and desktop publishing tools; by using various communication tools between PCs and *Apollo* workstations, we have also been able to enhance our use of numerous PC-based word-processing, drawing and general tools.

Because the workstations are connected by the Apollo token-ring network, file transparency is achieved for all of the members of the Institute. There are also gateways on each sub ring through which Apollos communicate with the computers in various departments at IU and with the BACS central computers by Ethernet. Part of the communication also employs a campus network called SYTEK which provides a high-speed datatransfer, and remote login links with other computers on campus.

Links with the rest of the world are possible through the *AIE* (Academic Information Environment) on the campus Vax-based system. We have access to Arpanet, Bitnet, Dow Jones, the NCSA (National Center for Supercomputing Applications), Telenet and Tymnet. This has greatly enhanced collaborations between the members of the Institute and researchers outside the university.

Our computer system is still under development but it appears that it will be able to do most of the jobs for which it was designed. At the present time, the system is about 80% complete and its uptime is more than 90% of the total work time, due to the contributions of technicians in various departments and the central support provided by *the Institute for the Study of Human Capabilities*.

7.4 Physical space

During its first two years of operation the Institute's physical facilities were mainly those portions of the eleven affiliated laboratories devoted to Institute supported research, conference rooms provided by the Department of Psychology, and temporary office space in the Department of Speech and Hearing Sciences. Remodeling of offices and a conference room in the university-owned Poplars Research and Conference Center will be completed by mid-summer, 1989, and will provide working space for the Institute's administration, visiting scientists, and computer systems programmers, and space for seminars and research-planning meetings. Two new Institute-supported research facilities have also been completed, one located in the Psychology Building, the other in the Visual Sciences Department of the School of Optometry (as described above).

8. Institute-Sponsored Seminars

October 27, 1988 – Sue Fallon, doctoral candidate, Indiana University – "Discriminability of Complex Sounds"

December 15, 1988 – Donald E. Robinson, Professor of Psychology, Indiana University – "Combined Detection Systems: Computer Aided Decision Making"

February 7, 1989 – Armin Kohlrausch of the Drittes Physikalisches Institut of the Universitat Gottingen – "Learning Effects in Hearing"

March 28, 1989 – Arthur Bradley, Assistant Professor of Visual Sciences, The School of Optometry, Indiana University – "Optics and Other 'Gunk:' Pre-neural Filters in the Human Visual System"

April 4, 1989 – S. Lee Guth, Professor of Psychology and Visual Science, Indiana University – "Toward the Ultimate Color Theory"

April 11, 1989 – Donald E. Robinson, Professor of Psychology, Indiana University – "Information Integration in the Auditory System"

April 18, 1989 – Professor Charles S. Watson and Assistant Professor Diane Kewley-Port of the Speech and Hearing Sciences Department, Indiana University – "Training Aids for Hearing Impaired Persons"

April 25, 1989 – James C. Craig, Professor of Psychology, Indiana University – "Tactile Channels"

June 16, 1989 – Dr. Mark Cannon, Staff Scientist, Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base – "A Model for Contrast Perception in Human Vision"

9. Extramural Activities

C. S. Watson is the director of the Institute for the Study of Human Capabilities and serves as an advisor to the National Research Council's Committee on Hearing, Bioacoustics and Biomechanics (CHABA). He is currently chairman, CHABA Working Group 95, on Personal Speech Perception Aids for the Hearing Impaired. He is also a member of ASA Standards Committees S3-63 on Acoustical Warning Devices, and S3-76 on Computerized Audiometry. Watson serves as a reviewer for the *Journal of the Acoustical Society of America*, *Journal of Speech and Hearing Research*, and *Perception and Psychophysics*.

J. C. Craig is the Associate Director of the Institute for the Study of Human Capabilities. He serves as a member of special review panels of NSF, NIH, and SBIR as well as having been a member of the NIH Study Section on Sensory Disorders and Language. He recently served on the Task Force on the National Strategic Research Plan for the new National Institute on Deafness and Other Communication Disorders. He is the recipient of the NIH's Javits Neuroscience Investigator Award, July, 1986 – June 1993.

A. Bradley serves as a scientific referee for *Vision Research, Journal of Neurophysiology, Journal of the Optical Society of America, Investigative Ophthalmology and Visual Science*, the *American Journal of Optometry and Physiological Optics*, and *Clinical Vision Research* and Butterworth Publishers.

N. J. Castellan, Jr. is the Associate Editor of *Computers and the Social Sciences*, and on the Editorial Boards of *Organizational Behavior and Human Decision Processes, Behavioral Decision Making*, and *Social Science Computer Review*.

S. L. Guth is an ad hoc member of the U.S. Committee of the International Commission on Illumination and a Fellow of the Optical Society of America. He is a referee for grant proposals submitted to NIH and NSF as well as a referee for articles submitted to *Journal of the Optical Society of America, Vision Research, Psychological Review, Journal of Experimental Psychology, Perception, Journal of Color Research and Application, Perception & Psychophysics*, and *Science*.

L. Humes was appointed this year to the Executive Committee of CHABA for a 3-year term. He continues as an Associate Editor of the *Journal of Speech and Hearing Research* and as a member of the Technical Committee on Psychological and Physiological Acoustics of the Acoustical Society of America. He continues to be supported, in part, by a Research Career Development Award from NINCDS.

D. Kewley-Port is Associate Editor for Speech Processing and Communication Systems of the *Journal of the Acoustical Society of America*. She referees grant proposals for NSF and has served as a member of a SBRI review panel. She also reviews manuscripts for the *The Journal of Speech and Hearing Research, Language and Speech*, and *IEEE Transactions on Acoustic, Speech and Signal Processing*.

G. Kidd is a member of the American Psychological Society, the Acoustical Society of America, the International Society for Ecological Psychology, and an associate member of the Psychonomic Society. He has reviewed manuscripts for the Journal of Experimental Psychology: Human Perception and Performance, Language and Speech, and the American Journal of Psychology.

Daniel P. Maki is a member of the American Mathematical Society, the Society for Industrial and Applied Mathematics, and the Acoustical Society of America and is a Governor of the Mathematical Association of America.

Robert F. Port is a member of the Linguistic Society of America, the Acoustical Society of America, the Association for Computational Linguistics, and the International Neural Network Society. He reviews manuscripts for the *Journal of the Acoustical Society of America*, the *Journal of Speech and Hearing Research, Perception and Psychophysics,* and the *Journal of Phonetics*.

D. Robinson continues to serve as a scientific advisor to CHABA and on the Science Advisory Board of the Parmly Hearing Institute, Loyola University, Chicago. In the last year, he presented an invited lecture at The Central Institute for the Deaf, St. Louis, MO and served as an invited panel member at the annual meeting of the Hugh O'Brian Youth Foundation, DePauw University, Greencastle, IN. He has reviewed papers for the *Journal of the Acoustical Society of America*, the *Psychological Bulletin*, and *Developmental Psychobiology*.

R. M. Shiffrin serves on the governing boards of the Psychonomic Society and the Society for Mathematical Psychology and is a consulting editor for *Memory and Cognition*, and *Acta Psychologias*. In 1987 he was the chair of the governing board of the Psychonomic Society and the Acting Director of Indiana University's Cognitive Science Program.

R. A. Suthers is on the editorial board of *Experimental Biology* and is a reviewer for the *Journal of Comparative Physiology, Ethology, Animal Behavior, Science, Behavioral Ecology & Sociobiology,* and the *Canadian Journal of Zoology*. He has been an invited lecturer at numerous national and international symposia.

L. Thibos serves as editorial reviewer for the *Journal of the Optical Society of America*, the *American Journal of Optometry and Physiological Optics*, and *Vision Research* and as a grant reviewer for the Air Force Office of Scientific Research, the National Science Foundation, and the National Health and Medical Research Council of Australia. He is a member of the national program committee for the 1989 annual meeting of the American Academy of Optometry. In July 1989 he was promoted to Associate Professor with tenure by Indiana University and was elected faculty presider by the School of Optometry.

10. Other Sources of Support

Auditory Research

AFOSR – 87-0300
9/1/87 – 9/30/90

Perception of Complex Auditory Patterns
C. S. Watson   – $390,411

NAVY(NWC) – N60530-88-C-0214,
7/1/88 – 6/15/89

Human and Expert Decision Systems – extension
D.E. Robinson   – $20,313

NIH (NINCDS) K04 NS01189
12/1/86 – 11/30/89

Speech Recognition Dificulties of the Hearing Impaired
L. E. Humes   – $165,000

NIH (NINCDS) R01-NS14709 (subcontract)
7/1/89 – 6/30/94

Frequency Analysis in Normal and Impaired Listeners
L.E. Humes   – $138,792

NIH (NINCDS) R01 NS20606
12/1/87 – 11/30/92

Detection & Identification of Complex Auditory Signals
C. S. Watson   – $478,814

NSF EET-8419339
1/15/86 – 6/30/89

Indiana Speech Training Aid (ISTRA)
C. S. Watson   – $298,828

Cognition and Decision Making Research

NIH2R01MH12717
12/1/85 – 11/30/89

Information Processing, Search & Retrieval
Richard M. Shiffrin – $240,604

Vision Research

NEI R03EY07638-01
2/88 – 2/89

Perceptual Aliasing in Human Amblyopia
A. Bradley   – $25,000

NIH (NEI) R01-EY05109
4/1/88 – 3/31/89

Functional analysis of retinal ganglion cells
L. N. Thibos   – $66,419

Tactile Research

NIH PHSR01NS9783-18
7/1/86 – 6/30/93

Cutaneous Pattern Perception
J. C. Craig   – $997, 361

NIH (Creare, Inc. subcontracted to I.U.)
9/15/86 – 9/14/88

Tactile Aid to the Deaf
J. C. Craig   – $87,189

Medical Sciences Research

NSF BNS 85-19621   Physiology & acoustics of bird song
2/1/86 – 7/31/89   R. Suthers   – $213,392

NSF BNS 87-20192   Sonar tracking of moving targets by echolocating bats
2/1/88 – 7/31/91   R. Suthers   – $267,151

Connectionist Models of Sensory and Cognitive Processes Research

NSF DCR-85-05635   Equipment for Computing Research
7/1/86 – 6/30/87   R. Port   – $99,331

NSF DCR-85-18725   Data Driven Speech Recognition Using Prosody
9/1/86 – 3/30/88   R. Port   – $210,560

11. Bibliography

The following is a cumulative list of articles published by Institute investigators from
September 1, 1988 to June 30, 1989

11.1 Articles and Book Chapters

1988

43   Campbell, K.A. & R.A. Suthers. (1988). Predictive tracking of horizontally moving targets by fishing bat, Noctilio leporinus. In: P. Nachtigal and P. Moore (eds.) *Animal Sonar: Processes and Performance*. Plenum Press. 501-506.

44   Craig, J.C. (1988) The role of experience in tactual pattern perception: A preliminary report. *International Journal of Rehabilitation Research*, 11, 167-171.

45   Hartley, D.J. & R.A. Suthers. (1988). The vocal tract acoustics of the horseshoe bat *Rhinolophus hildebrandti*. *J. Acoust. Soc. Amer.* 84: 1201-1213.

46   Hartley, D.J. & R.A. Suthers. (1988). The angular dependence of range precision in a broadband FM bat. In: P. Nachtigal and P. Moore (eds.) *Animal Sonar: Processes and Performance*. Plenum Press. pp. 275-279.

47   Howarth, P.A., Zhang, X.X., Bradley, A., Still, D.L. and Thibos, L.N. (1988) Does the chromatic aberration of the eye vary with age? *J. Opt. Soc. Amer.* A 5, 2087-2092.

48   Humes, L.E., Espinoza-Varas, B. & Watson, C.S., (1988). Modelling sensorineural hearing loss. I. Model and retrospective evaluation. *J. Acoust. Soc. Am.*, 83, 188-202.

49   Port, R., William Reilly & Daniel Maki (1988) Use of syllable-scale timing to discriminate words, *Journal of the Acoustical Society of America*, 83, 265-273.

50   Shiffrin, R.M. (1988). Attention. In R.C. Atkinson, R.J. Hernstein, G. Lindzey, and R.D. Luce (Eds.), *Stevens' Handbook of Experimental Psychology, 2nd Edition*, New York:Wiley.

51   Shiffrin, R. and Czerwinski, M.P. (1988). A model of automatic attention attraction when mapping is partially consistent. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 14, 562-569.

52   Shiffrin, R. and Thompson, M. (1988). Moments of additive functionals defines on semi-Markov processes. *Journal of Mathematical Psychology*, 32, 313-340.

53   Suthers, R.A. (1988). The production of echolocation signals by bats and birds. In: P. Nachtigal and P. Moore (eds.) *Animal Sonar: Processes and Performance*. Plenum Press. pp. 23-45.

54   Suthers, R.A. & D.W. Hector. (1988). Individual variation in vocal tract resonance may assist oilbirds recognizing echoes of their own clicks. In: P. Nachtigal and P. Moore (eds.) *Animal Sonar: Processes and Performance*. Plenum Press. 87-91.

55   Watson, C.S. and Kewley-Port, D. (1988). "Some remarks on Pastore (1988)," *J. Acoust. Soc. Am.*, 84, 2266-2270.

56   Craig, J. C. (1989) Interference in tactile localizations *Perception & Psychophysics*, **45**, 343–355.

57   Espinoza–Varas, B. and Watson, C.S. (1989). Perception of complex auditory patterns by humans. In S.H. Hulse and P. Dooling (Eds.) *The Comparative Psychology of Complex Acoustic Perception*, Lawrence Erlbaum, Hillsdale, NJ.

58   Gasser, M. (1989). Connectionism and universals of second language acquisition. *Studies in Second Language Acquisition*, **12**, (in press).

59   Hartley, D.J. & K.C. Campbell & R.A. Suthers. (1989). The acoustic behavior of the fishing bat, *Noctilio leporinus* during prey capture. *J. Acoust. Soc. Amer.* (In press)

60   Hartley, D.J. & R.A. Suthers. (1989). The emission pattern of the echolocating bat. *Eptesicus fuscus. J. Acoust. Soc. Amer.* (In press)

61   Hartley, R.S. & R.S. Suthers. (1989). Airflow and pressure during canary song: Direct evidence for minibreaths. *J. Comp. Physiol. A.* **165**: 15–26.

62   Horner, D.T., & Craig, J.C. (1989). A comparison of discrimination and identification of vibrotactile patterns. *Perception & Psychophysics*, **45**, 21–30.

63   Humes, L.E. and Jesteadt, W. (1989). Models of the additivity of masking. *J. Acoust. Soc. Am.* **85**, 1285–1294.

64   Humes, L.E. Masking of Tone Bursts by Modulated Noise in Normal, Noise–Masked Normal and Hearing–Impaired Listeners. *J. Speech Hear. Res.*, (in press).

65   Kewley–Port, D. and Atal, B. (1989). "Perceptual differences between vowels located in a limited phonetic space," *J. Acoust. Soc. Am.*, **85**, 1726–1740.

66   Ochs, M.T., Humes, L.E., Ohde, R.N., & Grantham, D.W. (1989). Frequency discrimination ability and stop–consonant identification in normally hearing and hearing–impaired subjects. *J. Speech Hear. Res.*, **32**, 133–142 .

67   Port, Robert (1989, in press) The fuzzy–logic model of perception: A teaspoon for a pyramid. *Brain and the Behavioral Sciences*, **12** (4).

68   Port, Robert and Crawford, Penny (1989). Incomplete neutralization and pragmatics in German. *Journal of Phonetics*, **17** (in press).

69   Scott, D. and Humes, L.E. (1989). Psychophysical modulation transfer functions: A comparison of three measurement methods. *J. Speech Hear. Res.* **32**, (in press).

70   Shiffrin, R.M., Murnane, K., Gronlund, S., and Roth, M. (1989). On units of storage and retrieval. In C. Azawa (Ed.), *Current Issues in Cognitive Processes: The Tulane Flowerree Symposium on Cognition*, Hillsdale, NJ:Erlbaum.

71   Watson, C.S. and Kewley–Port, D. (1989) "Computer–based speech training (CBST): Current status and prospects for the future," in *1989 Monograph on Sensory Aids for Hearing–Impaired Persons*, N. McGarr (Ed.), *Volta Review*, (in press).

72   Watson, C.S., Reed, D., Kewley–Port, D., and Maki, D. (1989). "The Indiana Speech Training Aid (ISTRA) I: Comparisons between human and computer–based evaluation of speech quality," *J. of Spch. Hearing Res.*, **32**, 245–251.

73   Wilde, G. & Humes, L.E. Application of the articulation index to the speech recognition of normal and impaired listeners wearing hearing protection. *J. Acoust. Soc. Am.*, (in press).

11.2 Technical Reports and
Abstracts of Papers Presented at Scientific Meetings

1988

21   Anderson, Sven, John Merrill and Robert Port (1988) Dynamic Speech Categorization with Recurrent Networks, In G. Hinton, T. Sejnowski & D. Touretzky (eds.) *Proceedings of 1988 Connectionist Summer School* (Morgan Kaufmann, San Mateo, Cal.) 1988, pp.398–406.

22   Anderson, Sven, John Merrill and Robert Port. (1988) Sequential Networks as Attentional Systems. *Presented at the first meeting of the International Neural Network Society.*

23   Bradley, A. and Thibos, L.N. (1988) Perceptual aliasing in human amblyopia. *Invest. Ophthal. Vis. Sci.* **29** (suppl.), 76.

24   Bradley, A., Zhang, X. and Thibos, L.N. (1988) Retinal image isoluminance is compromised by lateral and longitudinal chromatic aberration. *J. Opt. Soc. Am.* **A4**, (suppl.).

25   Jesteadt, W. & Humes, L.E. (1989). Effect of threshold on the growth of loudness at low frequencies. *J. Acoust. Soc. Am.* **85**, S108.

26   Kewley–Port, D., Watson, C.S., Elbert, M. The Indiana Speech Training Aid (ISTRA). *J. Acoust. Soc. Am., Supp I,* **84**, *S42,* presented at the 2nd joint meeting of The Acoustical Societies of America and Japan, Honolulu, Hawaii, November, 1988.

27   Kewley–Port, D., Watson, C.S., Elbert, M., and Cromer, P. Indiana Speech Training Aid (ISTRA). *ASHA* **30**, 207, Scientific Exhibit presented at the 1988 Annual Convention of the American Speech–Language–Hearing Association, Boston, MA, November 1988.

28   Port, Robert, Sven Anderson and John Merrill (1988) Temporal Information and Memory in Connectionist Networks, *Technical Report 265, Indiana University Computer Science Department.*

29   Still, D.L. and Thibos, L.N. (1988) Aliasing is the difference between pattern detection and pattern resolution in peripheral vision. *Amer. J. Optom. Physiol. Optics* **65**, (122P).

30   Thibos, L.N. and Still, D.L. (1988) Aliasing and contrast sensitivity in peripheral vision. *J. Opt. Soc. Am.* **A4**, (suppl.).

31   Thibos, L.N. and Still, D.L. (1988) What limits visual resolution in peripheral vision? *Invest. Ophthal. Vis. Sci.* **29** (suppl.), 138.

32   Watson, C.S., Kewley–Port, D. Computer–Based Speech Training Aids. *J. Acoust. Soc. Am., Supp I,* **84**, *S42,* presented at the 2nd joint meeting of The Acoustical Societies of America and Japan, Honolulu, Hawaii, November, 1988.

33   Zhang, X., Bradley, A. and Thibos, L.N. (1988) Achromatizing lenses may increase chromatic aberration in the retinal image. *Invest. Ophthal. Vis. Sci.* **29** (suppl.), 446.

34 Zhang, X., Bradley, A. and Thibos, L.N. (1988) Interaction between longitudinal and lateral chromatic aberrations in the retinal image. *J. Opt. Soc. Am.* A4, (suppl).

35 Zhang, X., Bradley, A. and Thibos, L.N. (1988) The beneficial effect of longitudinal chromatic aberration. *Amer. J. Optom. Physiol. Optics* 65, (47P).

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36 Applegate, R.A., Bradley, A., Zeffren, B. and Van Heuven W.A.J. (1989) Psycholphysical evaluation of the foveal avascular zone (FAZ) sizer and foveola location. *Invest. Ophthalmol. and Vis. Sci.* 30 (suppl), p.410.

37 Berg, B.G. and Robinson, D.E. (1989). Nonuniform utilization of information in multiple observation tasks. *Abstracts of Midwinter Research Meeting, Association for Research in Otolaryngology.* p. 301.

38 Bradley, A., Applegate, R., Zeffren, B. and Van Heuver, W.J.A. (1989) Psychophysical evaluation of retinal vessels. *Opt. Soc. Am. Topical Meeting on Non-invasive Methods.*

39 Bradley, A., Thibos, L.N. and Zhang, X. (1989) Luminance artifacts in the retinal images of isoluminant color-modulated stimuli: effect of correcting axial chromatic aberration. *Invest. Ophthalmol. and Vis. Sci.* 30 (suppl), p. 507.

40 Gasser, M. (1989). Robust lexical selection in parsing and generation. *Proceedings of the Eleventh Annual Meeting of the Cognitive Science Society.*

41 Guth, S.L. (1989) Unified model for human color perception and visual adaptation. (1989). *Proc. SPIE.*

42 Guth, S.L. (1989) Model for color vision and adaptation. *Invest. Ophthal. Vis. Sci.* (Suppl.) 30, 219.

43 Hartley, D.J. & K.A. Campbell & R.A. Suthers. (1989). The acoustic behavior of the fishing bat *Noctilio leporinus* during prey capture. *Association for Research in Otolaryngology.* Abstracts of the 12th Midwinter Research Meeting. p. 234.

44 Kewley-Port, D. Detection thresholds for isolated vowels. *J. Acoust. Soc. Am., Supp. 1*, 85, S51 presented at the 117th meeting of the Acoustical Society of America, Syracuse, NY, May, 1989.

45 Port, Robert and S. Anderson (1989, in press) Recognition of continuously performed melodies. *Proceedings of the Cognitive Science Society, Number 11.* (L. Erlbaum; NJ).

46 Still, D.L., Thibos, L.N., and Bradley, A. (1989) Peripheral image quality is almost as good as central image quality. *Invest. Ophthalmol. and Vis. Sci.* 30 (suppl.), p. 52.

47 Suthers, R.A. & R.S. Hartley. (1989). Differential airflow through the right and left sides of the avian syrinx during song. *Association for Research in Otolaryngology.* Abstracts of the 12th Midwinter Research Meeting. p. 308.

48 Thibos, L.N., Bradley, A. and Still, D.L. (1989) Visual acuity measured with clinical maxwellian view systems: effects of beam- entry location. *Optical Society of America Technical digest: Topical meeting on noninvasive assessment of the visual system*, 7, 94–97.

49 Ye, M., Zhang, X., Bradley, A. and Thibos, L. (1989) Chromostereopsis: The interaction of transverse chromatic aberration, axial chromatic aberration and the Stiles-Crawford effect. *Invest. Ophthalmol. and Vis. Sce.* **30** (suppl.), p. 507.

50 Zhang, X., Bradley, A., and Thibos, L.N. (1989) An estimation of the contrast contamination introduced by correction of ocular chromatic aberration. *Invest. Ophthalmol. and Vis. Sci.* **30** (suppl.), p. 219.